BATH AND WEST
— and —
Southern Counties Society

INSTITUTED IN 1777
FOR THE ENCOURAGEMENT OF

Agriculture, Arts, Manufactures and Commerce

FERTILIZERS DURING THE WAR AND AFTER

BY

E. M. CROWTHER, D.Sc., F.R.I.C.
Head of the Chemistry Department, Rothamsted Experimental Station, Harpenden, Herts.

Pamphlet No. 13

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FOREWORD.

By T. Wallace, M.C., D.Sc., F.R.I.C.
Director, Long Ashton Research Station.

With the end of the war in Europe it is possible to tell in part the war-time story of fertilizers and also to forecast some likely developments in their use in the immediate post-war period.

In their magnificent efforts to increase crop production during the war, farmers no doubt have often felt some measure of irritation, and sometimes even of frustration, at the rules and regulations governing supplies and uses of fertilizers on the farm.

It has been inevitable that the problems and burdens should have fallen unevenly and with different emphasis in different counties and on different farms, and, in particular, livestock farmers have felt considerable anxiety and maybe a sense of injustice at the official outlook on fertilizers for grass.

Dr. Crowther's article should do much to give the correct perspective to the problems of the war-time allocation and use of fertilizers from the national viewpoint and will possibly provide much food for thought to farmers regarding fertilizer practices on their own farms.

As Dr. Crowther has been very closely concerned with many aspects of fertilizer problems throughout the war period, and indeed has made considerable contributions to the solution of a number of them, he is able tc write as an authority on the subject.

The article which he has written for us forms an excellent objective account, full of hard facts, and deserves the closest study of all farmers concerned with crop production.

Mention of a few points from the text will arouse the interest of those who recognise that farming is a business which must be run on a solid basis of facts.

Crowther and Yates have summarised the main manurial experiments carried out prior to 1939 and suggested a basis for rational

manuring to accord with the results. Fertilizer Practice Surveys made during the war have shown how farmers use fertilizers, how County Committees think they should be used and the extent to which practices agree with actual crop and soil requirements. How far do current views on stored-up fertility in grassland agree with war-time experience? The problems of ploughed-out grass have furnished useful data on this point. Can economies be made in fertilizers? One answer to this has been provided by fertilizer placement experiments. Standardisation of compound fertilizers has been very successful during the war and should be seriously considered as a permanent feature. What is the value of returning straw to the land? The reply gives food for thought. Ground limestone is shown to be of great value as a source of lime, a fact which recalls the pioneer experiments of the Society carried out shortly after the last war.

And lastly the much-discussed subject of the effect of war-time cropping and manuring on soil fertility is dealt with. Has the over-all fertility declined? Dr. Crowther does not think so.

The article has yet another value. The factual data given will provide a valuable record for the future and in fact the contribution may prove to be in the nature of an historic document to members of the Society.

Our thanks and congratulations are due to Dr. Crowther for his able survey and for adding the story of fertilizers to the Society's list of special war-time pamphlets.

THE RESEARCH STATION,
LONG ASHTON, BRISTOL.

May, 1945.

NOTE ON THE SECOND EDITION.

The resetting of the type to meet the continued demand for this pamphlet has given an opportunity for a full revision. It has been possible to include figures for the annual consumption of fertilizers and liming materials, the revised prices of fertilizers and a summary of an agreed report on tenant-right valuation for residual manurial values. Some of the practical recommendations have been reviewed in the light of recent field experiments.

There can be no doubt that more fertilizers and liming materials must be used, especially on grassland, if the Agricultural Expansion Programme is to be carried through successfully. The fertilizer rationing scheme was based on the calculated requirements of the various crops and kinds of soil on each farm. If the war-time standards of efficiency in manuring and crop production are to be maintained, the established principles of manuring must now be understood and applied by farmers individually.

ROTHAMSTED EXPERIMENTAL STATION,
HARPENDEN, HERTS.

July 19th, 1948.

CONTENTS.

FERTILIZERS DURING THE WAR AND AFTER

By E. M. Crowther, D.Sc., F.R.I.C.

Head of the Chemistry Department, Rothamsted Experimental Station, Harpenden, Herts.

For the first year or so of the war farmers and County Committees were so preoccupied with securing the prescribed acreages of ploughed-up grassland that they had little time or thought for more technical questions. Agricultural colleges were closed, the activities of the county agricultural education services slumped and technical publications were suspended. But, as farmers settled down to the job of producing the maximum amount of food under new conditions of controlled cropping with fixed prices, limited supplies of labour and materials, and rapidly increasing mechanisation, many novel problems arose and called for technical advice. The changing outlook showed itself in the setting up of Technical Development Sub-Committees under the War Agricultural Executive Committees, in the rapidly increasing popularity of demonstrations, farm walks, discussions, "Brains Trusts" and conferences of all sorts, and later, in the flood of policies for post-war agriculture. On all sides it was agreed that whatever pattern British agriculture might assume after the war, the drive for greater technical efficiency must be maintained. Both on the individual farm and nationally steps had to be taken to review the effects of war-time changes, to make good inevitable deficiencies and to profit by the lessons of war-time experience. In this pamphlet an attempt is made to review fertilizer policy and practice in this way.

As a preliminary it will be necessary to consider suitable ways for describing the nature and strength of fertilizers. The pre-war consumption of fertilizers in Great Britain will be compared with that in neighbouring countries and the United States, and then the effects of the war on the need for fertilizers and the supplies available will be summarised. After describing briefly the basis of the fertilizer rationing scheme for England and Wales, an attempt will be made to show how the use of fertilizers should be related to the varying needs of crops, soils, previous manuring and the use of

dung. Recommendations based on results of field experiments will be compared with the war-time practice of farmers, and attention directed to a number of ways in which manurial practice should be modified to correct the deficiencies and to ensure the continued fertility of our land.

The exigencies of war-time have compressed into a few years advances in technique which might otherwise have taken decades. In some branches of industry—*e.g.* in aircraft and radio—new developments in research and technology can be put into operation as soon as blue prints are out, necessary plant assembled and staffs trained, but agricultural progress follows a different course. Even in this small country it involves hundreds of thousands of separate farms and holdings, each with its own complex problems, yet the war has shown very vividly how the pace can be speeded up by, first, obtaining reliable and comprehensive information in place of personal impressions and, then, putting the new policy clearly before the farmers who must carry it out.

Fertilizer Units.

Plants take up nutrients from soil almost exclusively as ions of simple salts, *e.g.* ammonium NH_4^+, calcium Ca^{++}, potassium K^+, sodium Na^+, magnesium Mg^{++}, nitrate NO_3^-, phosphate $H_2PO_4^-$ or HPO_4^{--}, sulphate SO_4^{--}, chloride Cl^-. They may also absorb small quantities of more complex inorganic or organic materials, but there is no evidence to show that these are essential for good crops in the way vitamins are for animals. Of the essential nutrient elements, nitrogen, phosphorus, potassium and calcium may be regarded as major ones, because they are taken up in large amounts and the supplies in the soil must often be supplemented by manuring. The other essential elements are generally provided in sufficient quantities by the soil, though occasionally it may be necessary to add sodium, magnesium, manganese or boron, either in fertilizers or sprays, to crops showing deficiencies characteristic for these elements.

Nitrogen fertilizers, of which sulphate of ammonia is the leading form, help general growth and leaf production. Phosphate fertilizers promote quick rooting, good establishment and early ripening, and are needed for clovers and root crops, particularly swedes. Potassium fertilizers are of special importance for fruit, potatoes and other root crops, and clovers. Soils may be so short of one or other of these three major plant nutrients that all crops will need the appropriate fertilizer. Calcium occupies a unique position among plant nutrients because it is supplied in basic forms, as in lime or limestone, to prevent soil from becoming too acid. As

dressings of lime have commonly to be measured in tons per acre and depend much more on the state of the soil than the crop to be grown, it is customary to treat liming materials as soil improvers rather than fertilizers.

Fertilizers differ so widely in their contents of plant nutrients that it is necessary to allow for their strength in planning manuring schemes, in costing alternative forms, and, above all, in rationing for widely differing systems of farming. Among "straight" fertilizers triple superphosphate is nearly three times as strong as ordinary pre-war superphosphate; high-grade muriate of potash is four times as strong as the old kainit; some of the concentrated compound fertilizers are well over twice as strong as ordinary compounds. It would have been quite impracticable to ration all these fertilizers merely on a tonnage basis.

By general convention the contents of plant nutrients are expressed as parts of nitrogen (N), phosphoric acid (P_2O_5) and potash (K_2O) in a hundred parts of fertilizer. It is also customary to use the old term "plant foods" in place of "plant nutrients" in referring to fertilizer analyses and statistics. Thus, the sum of the percentages of $N + P_2O_5 + K_2O$ is sometimes termed the "total plant food content" of a fertilizer and the ratio of the percentages for $N : P_2O_5 : K_2O$ (with N taken as 1.0) may be termed the "plant food ratio." The words "plant food" are also often used loosely in referring to the amounts of nutrient elements in soils, fertilizers and manures. There is little risk of confusion provided it is remembered that the name and the units employed are purely conventional; they are not intended to indicate the forms in which nutrient elements occur in soils or are taken up by plants.

It is convenient to use cwts. of plant foods (N, P_2O_5 and K_2O) as units for rationing schemes. To use cwts. per acre for describing field dressings leads to easier arithmetic than working in lbs. per acre. Some farmers may have been puzzled when they first met these terms and units in their fertilizer permits, but they will find them easier to follow in invoices and in working out manuring programmes if they remember that

1 cwt. N equals about 5 cwt. sulphate of ammonia (21% N).
1 cwt. P_2O_5 equals about 5 cwt. superphosphate (18% water-soluble P_2O_5).
1 cwt. K_2O equals about 2 cwt. (actually 1⅔ cwt.) muriate of potash (60% K_2O).

If the fertilizer permits helped to make these terms more generally understood, they may well have done more than the Fertilisers and Feeding Stuffs Acts achieved over decades in directing the farmer's

attention to the true basis for valuing and using the fertilizers which are offered to him in a bewildering variety of forms.

It may be necessary to issue a word of warning about muddles which may sometimes arise through the unfortunate survival of other old-fashioned terms. The Fertilisers and Feeding Stuffs Act, 1926, laid it down that all analyses in fertilizer warranties were to be made only as *nitrogen*, *phosphoric acid* and *potash*, but current market returns still use other expressions for certain imported organic fertilizers: "ammonia" (NH_3) in place of "nitrogen" (N), and "phosphate or tribasic phosphate of lime" ($Ca_3\,P_2O_8$) in place of "phosphoric acid" (P_2O_5). Some farmers and merchants still use these old terms in conversation and in verbal quotations. Thus, ordinary superphosphate is sometimes said to be "40% super," but it is most important to avoid confusing this grade (18% P_2O_5, which equals 39% $Ca_3\,P_2O_8$) with the modern triple superphosphate (48% P_2O_5, which in the old terms would be about 105% $Ca_3\,P_2O_8$).

The more critical farmer and the harassed typist in a merchant's or a County Committee office may rightly ask "Why bother about all the O's and the little figures, and not use plain P and K?" The persistence of the old terms is partly due to the mistaken idea that there is something remotely academic in talking about chemical elements, partly to the desire to make analyses look bigger, but mainly to the traditional survival in agricultural and industrial chemistry of the nomenclature of a century ago. It is to be hoped that before long fertilizer units may be simplified to plain N, P and K, but the clumsy old units may linger on as they are firmly embedded in numerous commercial conventions and official regulations. In the meantime a short conversion table is given for reference :—

1	part	N	(nitrogen).
= 1·21	parts	NH_3	(ammonia).
1	part	P_2O_5	(phosphoric acid).
= 2·19	parts	$Ca_3P_2O_8$	(tribasic phosphate of lime).
= 0·44	parts	P	(phosphorus).
1	part	K_2O	(potash).
= 1·85	parts	K_2SO_4	(potassium sulphate).
= 1·59	parts	KCl	(potassium chloride).
= 0·83	parts	K	(potassium).
1	part	CaO	(calcium oxide).
= 1·32	parts	$Ca(OH)_2$	(calcium hydroxide).
= 1·78	parts	$CaCO_3$	(calcium carbonate).
= 0·71	parts	Ca	(calcium).

The main inorganic nitrogen fertilizers consist of ammonium salts or nitrates. These behave in much the same way in the soil, and plants absorb either form. Ammonium (whether added in sulphate of ammonia or split off from organic fertilizers) is first held on the surface of fine soil particles or humus, and then converted into nitrate by soil bacteria. Nitrates, added in nitrate of soda or produced from ammonium, remain free in the soil water and are easily washed out.

In phosphorus fertilizers the phosphorus is present either as simple phosphates or in more complex forms, which may break down to simple phosphates in the soil. It is convenient to describe all these materials as "phosphates" and to speak of "available phosphates" in soils, provided it is remembered that all soil and fertilizer analyses are to be expressed either conventionally as "phosphoric acid" (P_2O_5) or preferably as "phosphorus" (P).

Both in fertilizers and soils potassium is present as a simple ion, but it is common practice to speak of "potash" in soils and fertilizers. Analyses are expressed as "potash" (K_2O) though "potassium" (K) would be better.

Pre-war Use of Fertilizers.

Before the war Great Britain used only modest amounts of fertilizer by comparison with several of the nearby countries with broadly similar climates and systems of farming. Figures are given in Tables 1 and 2 for the total pre-war consumption of fertilizers, expressed as plant foods, for the six European countries with the heaviest rates of manuring and for the main regions of U.S.A. The average rates of dressing are obtained by dividing the total amounts of fertilizer by the acreages of arable land.

European Countries.

The European countries in Table 1 are arranged in decreasing order for total plant foods per arable acre (Switzerland, which would occupy the fourth place, is omitted because so large a proportion of its total was used on grassland). The average rates of manuring varied very markedly from country to country, in accordance with the general intensity of farming and with the proportion of market gardening. Holland used over five times, Belgium three times and Germany over twice as much fertilizer per arable acre as Great Britain. It is well known that the average yields of crops in Holland and Belgium were much above those in Great Britain, and, although it would be wrong to ascribe this solely to heavier manuring, it is clear that in intensifying British agriculture

TABLE 1.

FERTILIZER CONSUMPTION IN EUROPEAN COUNTRIES 1936, EXPRESSED IN PLANT FOOD UNITS.

	Total amounts in thousand tons.			cwts. per acre arable land.				Plant food ratios.		
	N	P_2O_5	K_2O	N.	P_2O_5	K_2O	Sum.	N	P_2O_5	K_2O
Holland	62	95	92	0·54	0·82	0·80	2·16	1	1·5	1·5
Belgium	56	55	46	0·42	0·41	0·35	1·17	1	1·0	0·8
Germany	483	623	961	0·20	0·26	0·40	0·86	1	1·3	2·0
Denmark	35	65	36	0·11	0·20	0·11	0·41	1	1·9	1·0
Great Britain	66	188	74	0·08	0·22	0·08	0·38	1	2·8	1·1
France	144	387	217	0·05	0·15	0·08	0·28	1	2·7	1·5

TABLE 2.

FERTILIZER CONSUMPTION IN THE UNITED STATES 1939, EXPRESSED IN PLANT FOOD UNITS.

	Total amounts in thousand tons.			cwts. per acre arable land.				Plant food ratios.		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	Sum.	N	P_2O_5	K_2O
All U.S.A.	343	634	356	0·02	0·04	0·02	0·08	1	1·8	1·0
Main Regions.										
New England	15	28	24	0·08	0·16	0·14	0·38	1	1·9	1·6
Middle Atlantic ...	30	121	55	0·04	0·14	0·07	0·25	1	4·0	1·8
Southern	224	330	195	0·04	0·06	0·04	0·14	1	1·5	0·9
Mid-West	18	114	53	0·00	0·01	0·01	0·02	1	6·3	2·9
Western	27	29	8	0·02	0·02	0·00	0·04	1	1·1	0·3

we shall have a long way to go before we reach Belgian or Dutch standards.

The differences between countries would, however, not be quite so great if it were possible to assemble data for the total consumption of plant foods in all forms. Both Great Britain and Denmark

based their agriculture on livestock with cheap imported feeding stuffs, and the land received in consequence large amounts of additional plant foods from manurial residues. In the United Kingdom before the war farmers bought by the way of imported feeding stuffs three times as much nitrogen as in all nitrogen fertilizers, as much phosphoric acid as in superphosphate and nearly as much potash as in all potassium fertilizers. The total plant food contents of fertilizers and imported feeding stuffs are given in Table 3. How much of these vast quantities of plant food reached

TABLE 3.

PLANT FOOD CONTENTS OF ANIMAL FEEDING STUFFS IMPORTED INTO UNITED KINGDOM, AVERAGE OF YEARS 1934-8.

	Thousand tons.			
	Product.	N	P_2O_5	K_2O
Maize, wheat offals and cereals	6490	124	80	48
Cakes and meals	1730	87	29	24
		211	109	72
Plant foods used in fertilizers (G.B. and Ireland, 1936) ...		66	188	74

the land depended largely on the way the farmyard manure was made and used. Much of the nitrogen and potassium was lost down the drains, and many stock and dairy farmers had too little arable land on which to allow the remainder to give good returns. In Denmark livestock were maintained mainly on arable land, and liquid manure was collected separately and used directly on the arable land. The liquid manure alone supplied about twice as much nitrogen and four times as much potassium as were used in fertilizers.

Fertilizer practice in the six European countries listed in Table 1 also differed notably in the proportions in which the three plant foods were used. Great Britain used most phosphoric acid in proportion to nitrogen, and Belgium least. These figures illustrate a fairly general rule that as fertilizer practice develops with more intensified farming the ratio of nitrogen to other plant foods increases. (By this criterion British practice shot ahead during the war.) Germany was the only country to use more potash than phosphoric acid. In Holland and Belgium these two plant foods were used in similar amounts, but Great Britain and France used far more phosphoric acid than potash. The results of field experiments show that the average responses to unit nitrogen and

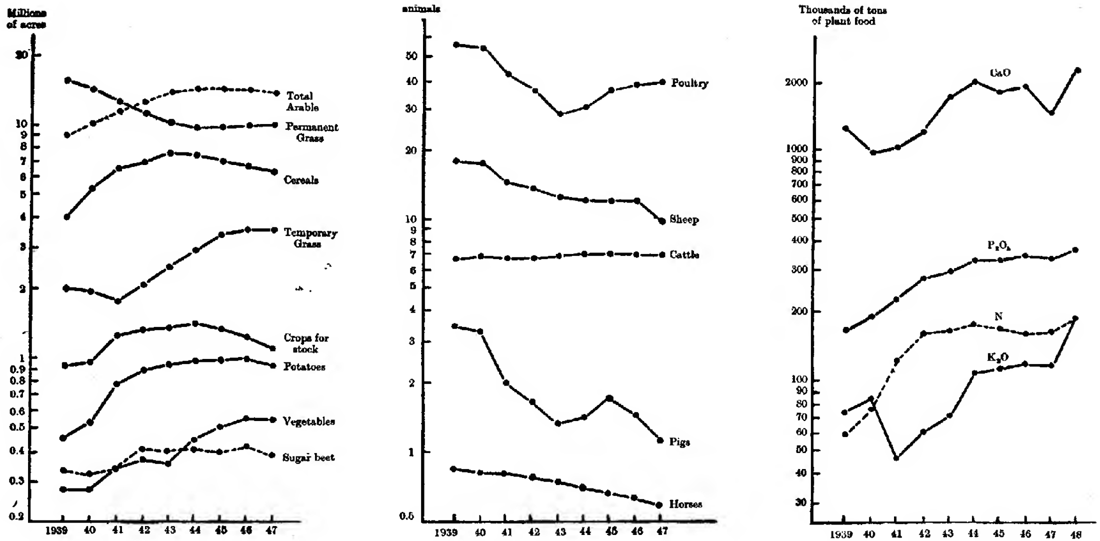

Fig. 1. ACREAGES OF CROPS AND GRASS IN ENGLAND AND WALES, NUMBERS OF LIVESTOCK IN ENGLAND AND WALES 1939 TO 1947, AMOUNTS OF FERTILIZERS AND LIMING MATERIALS IN UNITED KINGDOM, 1939 TO 1948 (logarithmic vertical scales).

(Crops for stock include peas and beans for stockfeeding, swedes, mangolds, kale, rape, cabbage, etc. for fodder. Fertilizer consumption for England and Wales is about 75 per cent of that for United Kingdom).

unit potash are much the same in the different countries. It follows, therefore, that these variations in fertilizer practice are determined more by the stage of agricultural development and commercial propaganda than by the intrinsic needs of soils and crops. There is room for much readjustment and improvement.

The United States.

The effects of more drastic differences in climate and types of agriculture may be illustrated by the figures in Table 2 for the pre-war fertilizer consumption in the main geographical regions of the United States. Before the war the whole of the United States used far less fertilizer than Germany alone, and over half of the total consumption was in the Southern region, especially in the cotton states. The average rates in the New England States and the Middle Atlantic region were much the same as in Great Britain and France, respectively, thus reflecting the rough similarities in their climate and types of agriculture. The Middle Atlantic and the Mid-West regions used high proportions of phosphoric acid relative to nitrogen, but very little of the land in the Middle West received any fertilizer at all.

In the three "Dust Bowl" states of Kansas, Colorado, and Oklahoma the average consumption of fertilizers was too small to show without lots of decimals in the terms adopted for Table 2. It was only about 1 cwt. of sulphate of ammonia, 15 cwts. of superphosphate and less than 0·5 cwts. of muriate of potash *per thousand acres of crop*. The "Dust Bowl" was caused by too frequent ploughing and not by too much fertilizer. The remedy will be found in more cover crops and leys, and, to establish these, much more fertilizer will be needed.

The Changing Needs of War-time.

War-time agricultural policy required maximum output of human food. Cereals, potatoes and vegetables were given the highest priority among crops. Since milk was also a first-priority food, more fodder crops had to be grown to replace the rapidly dwindling imports of feeding stuffs for animals.

The principal changes year by year from 1939 to 1947 are summarised in Figure 1, which shows the acreages of the principal crops and the numbers of farm animals in England and Wales and the consumption of fertilizers and liming materials (expressed as plant foods) in the United Kingdom. All the data are plotted so that equal slopes represent changes in the same proportion.

From 1939 to 1944 about one-tenth of the remaining permanent

grass was ploughed out each year. Cereals went up steeply for the first two years, reached a maximum in 1943 and then declined slowly. Potatoes and fodder crops increased rapidly in the second year of the war, and then temporary grass began to increase as farming settled down to its new pattern. The acreage of vegetables rose steadily from 1939 to 1947.

Apart from some increase in cereals at the expense of leys, the proportions of the principal arable crops had been restored by 1944 to about the 1939 balance, which happened to be very close to that for the old Norfolk rotation—half cereals, one-quarter ley, and one-quarter other crops, mainly roots.

Cattle numbers remained roughly the same throughout, but all other animals were drastically reduced. From 1940 to 1944 the number of horses fell by about one-fifth, sheep by one-third, poultry by nearly one-half and pigs by more than one-half. Before the war pigs and poultry depended largely on imported cereals, which could not be spared in war-time.

TABLE 4.

TOTAL PLANT FOOD CONTENTS OF THE PRINCIPAL CASH CROPS OF THE UNITED KINGDOM.

	Thousand tons.					
	N		P_2O_5		K_2O	
	1937	1943	1937	1943	1937	1943
Wheat grain	32	67	14	30	10	21
Barley grain	12	26	6	14	4	9
Potatoes	17	33	9	18	29	59
Sugar beet	5	7	2	3	2	2
TOTAL	66	133	31	65	45	91

The new cropping policy increased the need for fertilizers. Most of the ploughed-out grassland was deficient in lime and phosphate, and some of it in potash. The greatly increased acreage of root and green crops, especially those sold off the farm, increased the demands on the soil. The scale of the change is illustrated in Table 4. The drastic cuts in imported feeding stuffs greatly reduced the amounts of plant foods reaching the land as manurial residues.

The total consumptions of fertilizers and liming materials are shown as tons of plant food in Figure 1. Nitrogen fertilizers increased rapidly in the first three war-years and then remained steady. Phosphate fertilizers increased fairly regularly. Potassium fertilizers became very scarce by 1941 and then increased rapidly

till the end of the war. The statistics for fertilizers and liming materials will be considered in more detail in a later section (p. 49).

In following the post-war changes shown in Figure 1, it should be remembered that some of the low values for 1947, *e.g.* in liming materials, numbers of sheep and acreages of potatoes and other root crops, were the result of the prolonged frost and widespread floods in the spring of that year.

At the beginning of the war and again during spells of acute shipping shortage, the view was sometimes put forward that it might be better policy to import human foodstuffs for immediate consumption in place of fertilizers to produce extra food a year or so later. Had this been done a great deal of the labour, fuel and other materials put into the food production campaign, and especially into ploughing-up and reclamation, would have been wasted and the output of food seriously reduced.

Although there could be no doubt that abundant supplies of fertilizers were essential, the authorities had to solve many intricate problems before they could settle just how much fertilizer it was justifiable to import under all the fluctuating conditions of supply, transport and labour. New methods had to be developed for estimating the aggregate returns in food at different levels of imports, and for seeing that the imported materials would be used properly. Informed practical experience had to be supplemented by special fact-finding investigations. One of these dealt with the crop returns from fertilizers as shown in recorded field experiments, and another with the way in which farmers were actually using fertilizers. The results of these investigations will be considered below in some detail, because they bear directly on the post-war problems of individual farmers.

The war-time rationing of fertilizers aimed at more efficient production and not at some abstract principle of equitable distribution. With the ending of controls and permits the general problem of rationing passes from officials to individual farmers, who must obtain suitable supplies each season and allot them to individual fields. The general problem is closely akin to that of feeding dairy cows by providing the proper amounts of starch equivalent and protein equivalent for animals of different breeds, ages and milk yields, under conditions of fluctuating supplies and prices of feeding stuffs. Unfortunately the rules for good rationing are more difficult to define, since soils are more variable than cows.

FERTILIZER CONTROL AND RATIONING.

Immediately on the outbreak of war the Ministry of Supply set up a Fertiliser Control to deal with all fertilizers except sulphate of

ammonia, which came under the Industrial Ammonia Control. All producers of fertilizers were licensed and all distributors registered. Maximum prices were fixed, with a sliding scale reducing prices of sulphate of ammonia and superphosphate by 1/6 per ton per month below the March—June price in order to encourage earlier delivery. The following account of the system of fertilizer distribution refers particularly to England and Wales; somewhat different systems were adopted for Scotland and Northern Ireland.

Nitrogen Fertilizers.

Sulphate of ammonia was produced in sufficient quantities throughout the war to make restrictions unnecessary, except for one short spell at the end of 1943, when autumn applications to agricultural land were prohibited. Storage was the main difficulty. Factories had to work at full pressure throughout the year, but the farm demand reached an acute peak in spring. Factories could not store the greater part of a year's production, and transport services could not undertake to deliver a vast quantity shortly before farmers needed it. The bulk of the fertilizer had to be stored on farms, even though most of them were ill-equipped for the job. To spread deliveries more evenly a special Government Distribution Allowance was introduced in 1941. Each July a limited amount of sulphate of ammonia was offered at reduced prices for delivery at the manufacturer's convenience, the rebate being 28/- per ton in 1941 and 1942 and 15/- per ton in 1943 and 1944. Some farmers experienced considerable trouble with sulphate of ammonia which caked during storage at the farm, but it is difficult to see how this could have been avoided under war conditions. Similar problems will remain after the war, and the only remedy, apart from possible technical improvements in manufacture, will be to provide more and better storage facilities, both on farms and at merchants' depots.

Phosphate Fertilizers.

There was no formal control of phosphate fertilizers until the summer of 1941, and no general rationing scheme until the summer of 1942. By 1941 it had proved unsatisfactory to allow fertilizer sales to follow pre-war purchases because this penalized farmers with deficient soils and much newly ploughed-out grassland. The first steps in controlling distribution were to prohibit sales more than 60 days ahead, and to allot raw materials to manufacturers in accordance with allocations made to counties in terms of their cropping targets, taking into account varying needs of crops and soils. County War Agricultural Executive Committees were empowered to issue priority certificates to farmers otherwise unable

to obtain phosphates. Two counties, Norfolk and East Sussex, went further and rationed all their phosphates by permits to individual farmers, but in other counties the necessary adjustments, apart from priority certificates, were left to the merchants. To economize phosphate in compound fertilizers, limits were set to the ratio of phosphoric acid to nitrogen. It was also necessary to prohibit the use of phosphate fertilizers on all grassland, including established leys, because phosphates act slowly on grass, the full benefit being spread over a term of years. The future productivity of some grassland had to be sacrificed for the more immediate returns on the tillage land. The basic slag subsidy of one-quarter of the delivered cost was withdrawn on July 31st, 1941, the Government contribution going instead towards the fluctuating but increasing subsidy required to hold fertilizer prices constant.

By the summer of 1942 it was necessary to introduce a permit scheme for phosphates. The County Committees again received allocations based on their cropping targets, with allowances for the different needs of crops and the special requirements of deficient soils. Some County Committees followed similar methods in working out permits for individual farms, and others allowed a flat rate per acre for either all tillage crops or all arable land on the farm. These systems allowed every farmer to obtain at least a moderate supply, but sometimes they failed to distinguish sufficiently between different crops or between old arable and newly ploughed-out land.

For 1943-44 and 1944-45 phosphate permits were issued on a uniform basis for all farms in England and Wales. The farmer put in a special cropping forecast and received a permit to buy fertilizers containing a given number of cwt. P_2O_5. This quantity was calculated by allowing specified rates per acre for each crop, with separate allowances for all land known to be acutely deficient in phosphate and for all fields ploughed-out of grass since 1939. The details for 1944-45 are given for reference in Table 5. There were no restrictions on the way in which the farmer used the permitted quantity of phosphate on his tillage land. Thus, the low rate of 0·1 cwt. P_2O_5 per acre for cereals was not intended as a standard rate of application but as enough to ensure at least a modest supply for farms with a large proportion of cereals. Farmers were encouraged to apply more phosphate to cereals on exhausted land and to undersown crops. In 1943-44 the ban on phosphates for grass was modified to the extent of allowing the County Committees to make allocations for dairy pastures. The control and rationing of phosphate fertilizers were withdrawn on July 1st, 1946.

Potassium Fertilizers.

Potassium fertilizers required still more drastic treatment. In the summer of 1940 the total stocks were down to half a normal year's requirements, and the usual sources of supply were completely cut off. To avoid dissipating potash over a wide acreage at the expense of the crops and soils most needing it manufacturers were asked to continue their pre-war range of potato fertilizers, especially those with most potash. Potash was to be used only in compounds with at least 5% K_2O for ordinary materials and 10% K_2O for concentrated ones. The merchants were to ask for an assurance from their customers that potassium fertilizers would be used only for potatoes, sugar beet, flax and market garden crops. From December 1941 onwards, imported potash was restricted to certain priority crops by Control Orders, which specified maximum rates of dressing for each crop. The farmer was at liberty to vary the rates on different fields, provided the average for the whole acreage of a given crop did not exceed the maximum.

For 1941-42 the maximum rates in cwts. K_2O per acre were 0·6 for potatoes, onions, carrots and flax, 0·4 for sugar beet, 0·3 for black currants, market garden crops and for roots and vegetable grown for seed. The rate for potatoes was raised to 0·9 in 1942-43 and to 1·2 in 1944-45; that for sugar beet was reduced to 0·3 in 1943-44. Beans were added to the priority list in 1943-44, and mangolds and hops in 1944-45. A separate permit scheme was employed for tomatoes under glass. The 1944-45 rates for all permitted crops are shown in Table 5.

TABLE 5.

FERTILIZER RATIONING SCHEME FOR ENGLAND AND WALES, 1944-5.

P_2O_5 cwts. per acre.

- 3·0 tomatoes under glass.
- 0·7 potatoes, swedes, market garden crops (+0·3 for each subsequent crop), tomatoes in the open.
- 0·5 mangolds, peas, beans, sugar beet, roots and vegetables for seed, all other root and green crops for stock feeding, seeds for 3 year leys, hops.
- 0·3 small fruits, tree fruits (approved orchards only)
- 0·1 cereals, flax, seeds for 1 year leys.
- 0·1 all grass (over seven years) ploughed-out since 1939.

Additional allowances by County Committees for total area of phosphate-deficient land on the farm and for a part of the dairy pastures.

K_2O cwts. per acre.

- 4·2 tomatoes under glass (6 cwt. sulphate and 2 cwt. muriate of potash).
- 1·2 potatoes, tomatoes in the open, hops.
- 0·6 flax for fibre, roots and vegetables for seed.
- 0·3 mangolds, sugar beet, beans, market garden crops (with extra allowances for intensive cropping), black currants.

Additional allowance on special permits by County Committee for total area of potash-deficient land on the farm.

Separate permits were issued by County Committees for land known to be acutely deficient in available potash. This potash could, of course, be used for any tillage crop. No potash was allowed under any conditions for established grass or even for direct reseeding. The control and rationing of potassium fertilizers were withdrawn on July 1st, 1947.

Fertilizer Requirements of Crops.

The problem of distributing fertilizers to best advantage throughout a country is only a more general form of one which faces every farmer in drawing up his annual manuring programme. The principles worked out and established during the war may now be considered from this point of view. It will be convenient to deal, first, with the average needs of the principal crops and, then, with the various modifications according to climate, amount of dung used, special requirements of individual soils and fields and, finally, previous manuring. At this stage the discussion is confined to the immediate effects on the crop to which the fertilizer is applied. Residual effects are considered separately on page 31.

Farmers and merchants recognize the differing requirements of the principal crops when they describe certain kinds of mixed fertilizers as "potato manures," "corn manures," etc., but it appears that most of them make little or no allowance for all the other complicating factors. Farmers who generally use purchased compounds or home-made mixtures have little opportunity of knowing which one of the two or three major plant foods supplied is of most importance on particular occasions, and sometimes they generalize too far from outstanding observations. Thus, when a crop gets away well after a dressing of phosphate, they are apt to assume that the benefit will carry through to harvest and be repeated regularly on other fields, which may have quite different soils and manurial histories. Actual experiments often give very different results. It is, of course, extremely difficult to analyse all the complex effects of soil and season on the responses of crops to fertilizers, but the general requirements of the various crops can be obtained from large numbers of experiments spread over wide areas and many years. These will give results applicable to average land and capable of adjustment to local conditions.

Until recently, little progress had been made in summarising information hidden away in records of past experiments, apart from those at a few experiment stations. Most experiments had been carried out as isolated local ventures with no consistent theme or plan. The kinds and amounts of fertilizers tested had varied so much that there seemed no obvious way of drawing general averages.

Average Results of Fertilizer Experiments.

E. M. Crowther and F. Yates (*) showed how this difficulty could be overcome, and also how the results could be used to calculate the most efficient dressings of fertilizers for various conditions. It is well known that crops do not increase indefinitely with heavier manuring; if fertilizer dressings are increased by equal steps the amount of extra crop falls off regularly for each additional step. A simple mathematical expression for the "Law of Diminishing Returns" can be used to express the relationship between yield and amount of fertilizer, and so make it possible to combine results from a large number of experiments as average responses for different amounts of each of the three principal plant foods.

TABLE 6.

AVERAGE RESPONSES IN CWTS. CEREAL GRAIN OR TONS ROOTS PER ACRE TO INCREASING DRESSINGS OF FERTILIZERS IN THE ABSENCE OF DUNG.

Notes. 1. Phosphate effects are given for Central and Northern England and are close to the average for Great Britain. They should be reduced by one-third for the drier South and East, and increased by two-thirds for the wetter West and Scotland.

2. The average responses to fertilizers are less on crops receiving dung, the reductions being one-tenth for N, one-half for P_2O_5, and two-thirds for K_2O.

3. The heavier rates of nitrogen for cereals and swedes, enclosed in brackets, are too high for normal practice.

Plant food in cwts. per acre.	Cereals cwts.	Potatoes tons	Sugar Beet tons	Mangolds tons	Swedes tons
Nitrogen.					
0·2	3·0	0·8	0·8	2·6	2·0
0·4	4·8	1·4	1·4	4·1	3·1
0·6	(5·8)	1·7	1·7	5·0	(3·8)
0·8	(6·5)	1·9	1·9	5·6	(4·3)
1·0	(6·9)	2·0	2·0	5·9	(4·5)
Phosphoric Acid.					
0·2	0·5	0·5	0·4	1·0	1·8
0·4	0·9	0·9	0·7	1·7	3·1
0·6	1·1	1·1	0·9	2·2	4·0
0·8	1·3	1·3	1·0	2·6	4·6
1·0	1·4	1·4	1·1	2·8	5·0
Potash.					
0·2	0·4	0·6	0·3	1·8	1·2
0·4	0·6	1·0	0·5	3·1	2·0
0·6	0·8	1·2	0·6	4·0	2·5
0·8	0·9	1·4	0·7	4·6	2·9
1·0	1·0	1·6	0·8	5·0	3·2

* "Fertilizer Policy in War-time. The fertilizer requirements of arable crops," by E. M. Crowther and F. Yates, *Empire Journal of Experimental Agriculture*, Vol. IX, No. 34, pp. 77-97, 1941.

It was found that the average results of all experiments recorded since 1900 in Great Britain agreed fairly well with those of the much larger numbers of experiments in other Northern European countries, provided allowance was made for the fact that phosphates generally give larger returns in wetter areas.

The average results obtained in this way on four root crops and cereals are set out in Table 6 at different rates of application of N, P_2O_5 and K_2O to crops grown without dung. The phosphate effects tabulated refer to Central and Northern England, and are similar to those for Great Britain as a whole. Appropriate factors are given above the Table for adjusting the average responses for other districts and for use of dung. As has already been pointed out, the average results have been obtained from large numbers of experiments, mainly on commercial farms, and so refer to soils of average fertility and crops grown in normal rotations.

"Most Profitable Dressings."

The results in Table 6 show how the responses of five kinds of crop increase with successive equal steps in fertilizer dressings. Where the point is reached at which the cost of a little extra fertilizer is just repaid by the value of the extra crop, the fertilizer shows the maximum profit. The levels of these "most profitable dressings" naturally depend on the responsiveness of the crop and on its value per unit. Thus, it clearly pays to manure potatoes more heavily than cereals. For cash crops it is relatively easy to work out the "most profitable dressings," but for fodder crops it is more difficult to assess their value to the farmer, and thence the returns for given amounts of fertilizers. Calculations might be based on starch equivalent or any other unit, or prices per ton might be estimated by comparison with other foods. Table 7

TABLE 7.

"Most Profitable Dressings" of Fertilizers in cwts. Plant Food per acre at 1940 prices for Crops grown without Dung on average land. (phosphate rates for Central and Northern England).

Notes. 1. On dunged land *reduce* N by 0·04, P_2O_5 by 0·38, K_2O by 0·6.
2. In dry S and E regions, *reduce* P_2O_5 by 0·22.
3. In wet W and N regions, *increase* P_2O_5 by 0·28.
4. For cereals and swedes N to be *limited* to 0·4 in S and E or 0·2 in W and N.

	Cereals	Potatoes	Sugar Beet	Mangolds	Swedes
N	(0·62)	0·91	0·78	0·64	(0·61)
P_2O_5	0·24	1·32	0·91	0·74	1·18
K_2O	0·10	1·44	0·72	1·06	0·91

contains estimates of "most profitable dressings," made by Crowther and Yates in terms of 1940 prices for the conditions covered in Table 6. The adjustment to other conditions and also the residual values will be considered more fully in later sections.

The "most profitable dressings" are not very sharply defined, for there is a wide range over which the return in extra crop is close to the cost of extra fertilizer. Most farmers prefer to work somewhat below these "most profitable dressings," and make only slightly less profit on considerably less outlay. Further, these "most profitable dressings" are not to be regarded as ideal or generally recommended dressings, but as varying with values of crops, prices of fertilizers and restrictions on supplies, and thus needing to be revised from time to time. Their main use is to supply a series of figures for relative crop needs and a basis for adjusting dressings to local and current conditions. They are, in fact, index figures to serve as a sort of handicap or bogey. The essential point is that, to ensure the best aggregate returns, adjustments to other conditions should be made by *adding or subtracting roughly equal amounts for all crops*. Thus, if in 1940, it had been proposed to give 1·0 cwt. P_2O_5 per acre to potatoes (*i.e.* 0·3 below the "most profitable dressing"), sugar beet on similar land should have received about 0·6 cwts. P_2O_5 per acre, and cereals none. When supplies are short, all dressings should be cut down by an equal amount and not by an equal fraction. This principle, which formed the basis of the fertilizer rationing scheme, is, of course, only a formal expression of the sound farming practice of, first, meeting the most urgent needs and, then, raising the all-round level, but it has the advantage that it can be applied to a number of other problems which are less easy to solve.

Survey of Fertilizer Practice.

In Table 8 the "most profitable dressings" at 1940 prices, both with and without dung, are compared with the amounts used by farmers in the 1941-42 season, and with the amounts allotted to crops under the Fertilizer Rationing Schemes of 1943-44 and 1944-45. The figures from practice are based on a survey carried out by the Advisory Chemists in three Advisory Provinces in the North, East and West of England and analysed at Rothamsted.* In each county some 40 to 120 farms were selected at random, and on these farms old arable, new arable and permanent grass fields were again picked at random, and their recent manurial treatments

* F. Yates, D. A. Boyd and I. Mathison, "The Manuring of Farm Crops. Some results of a survey of fertilizer practice in England." *Empire Journal of Experimental Agriculture,* Vol. XII, p. 163-176, 1944.

TABLE 8.

COMPARISON OF "MOST PROFITABLE DRESSINGS" (AT 1940 PRICES) WITH AVERAGE PRACTICE IN SURVEYED COUNTIES AND WITH RATES USED IN FERTILIZER PERMITS.

1. Rates in cwts. plant food per acre.
2. The figures for average practice show the fraction of fields dressed with each kind of fertilizer, the "average actual dressing" on these fields and the "average overall rates" for the crop, including fields without the particular fertilizer.

		Most profitable dressings		Average rates in practice in 1941-2			Rationed rates (N not rationed)	
		No dung	With dung	% of fields dressed	Average actual dressing	Average overall rate	1943-4	1944-5
Cereals	N	(0·62)	(0·58)	60	0·26	0·16	—	—
	P_2O_5	0·24	nil	40	0·45	0·18	0·1	0·1
	K_2O	0·10	nil	2	0·21	0·00	nil	nil
Potatoes	N	0·91	0·87	83	0·60	0·49	—	—
	P_2O_5	1·32	0·94	80	0·78	0·62	0·7	0·7
	K_2O	1·44	0·84	67	0·60	0·41	0·9	1·2
Sugar Beet	N	0·78	0·74	93	0·53	0·49	—	—
	P_2O_5	0·91	0·53	90	0·61	0·55	0·5	0·5
	K_2O	0·72	0·12	69	0·48	0·33	0·3	0·3
Mangolds	N	0·64	0·60	74	0·40	0·30	—	—
	P_2O_5	0·74	0·36	67	0·60	0·40	0·5	0·5
	K_2O	1·06	0·46	21	0·40	0·08	nil	0·3
Swedes	N	(0·61)	(0·57)	69	0·29	0·20	—	—
	P_2O_5	1·18	0·80	83	0·60	0·50	0·7	0·7
	K_2O	0·91	0·31	13	0·34	0·04	nil	nil

examined in relation to their cropping histories and soil analyses. The survey has been extended to other areas, and in due course more representative averages will be obtained. It should be noted that the data given refer to a period of acute potash shortage, when potatoes and sugar beet were limited to 0·6 cwts. and 0·4 cwts. K_2O per acre respectively, and allocations for deficient soils were still very small relative to those for crops. The figures presented show the fraction of fields dressed with each fertilizer, the average actual rates on these fields and the average over-all rates, including fields without the particular fertilizer. From these tables, a farmer can compare his own practice both with the "most profitable dressings" at 1940 prices and with the general practice of other farmers. Where he deviates widely from both of these, he might well reconsider his practice and seek advice.

Cereals. The main need of cereals is nitrogen. It is not possible to give accurate estimates of the amounts used before the war,

but, in one survey of the manuring of potatoes and the immediately preceding crops, it was found that two-thirds of the cereal crops throughout the country received no nitrogen fertilizer. To illustrate the increases to be obtained from a more general use of nitrogen, Crowther and Yates calculated that in Great Britain, in the years immediately preceding the war, about £1 million were spent on nitrogen fertilizers for cereals, resulting in extra crops worth £4 million. If an average rate of 1 cwt. sulphate of ammonia per acre had been used on the pre-war cereal acreage, the extra crop would have been worth £11 millions for an outlay of £3 million; for twice this rate the extra crop would have been worth £17 million. The Survey of Fertilizer Practice showed that in 1942 about 60% of the greatly increased cereal acreage received the equivalent of 1¼ cwts. sulphate of ammonia per acre. This improvement on pre-war practice made a major contribution to the country's food supply and the farmers' profit.

Although under experimental conditions cereals respond well to heavy dressings of nitrogen, in practice it is often advisable to use lower rates to reduce the risk of lodging. Dressings of 2 cwts. sulphate of ammonia per acre in the drier south and east, and of 1 cwt. in the wetter west and north would generally be safe. Less nitrogen should be used for undersown cereals to avoid undue competition with the "seeds," and also on recently ploughed-out good grassland likely to be relatively rich in available nitrogen. More nitrogen may be used for second or third straw crops.

Crowther and Yates's conclusion from their analyses of field experiments that cereals grown on average old arable land in normal crop rotations did not pay for dressings of phosphate and potash elicited surprise in some quarters when it was first published. There can, however, be no doubt about its correctness. It would have been wasteful to import these fertilizers for cereals on normal land, for the ships could have brought over more wheat for immediate consumption than these fertilizers would have produced a year later. The Survey showed that about 40% of the cereals received phosphate, at an average dressing well above what would be justified for old arable land. This was due in part to the traditional use of compound fertilizers for cereals, especially on farms with only a small proportion of roots.

Potatoes. Experienced potato growers in Cambridgeshire and South Lincolnshire use heavy dressings of fertilizers, commonly 15 cwts. or more per acre, but some war-time growers used little or none, even though their soils were intrinsically poorer. Before the war compound fertilizers for potatoes generally had much more phosphoric acid than nitrogen or potash, and sometimes even

more than the nitrogen and potash together. The results of experiments show that potatoes should receive roughly equal amounts of these three plant foods, at least where dung is used. War-time changes in supplies brought the manuring of potatoes much more closely into line with the needs of the crop. In 1944-45 the fertilizer permit allowed 10 cwts. of a mixture supplying 0·7 cwt. N, 0·7 cwt. P_2O_5, and 1·2 cwt. K_2O per acre.

Sugar Beet. Sugar beet requires roughly equal amounts of the three major plant foods. If the land has been dunged the fertilizers should supply considerably more nitrogen than phosphoric acid or potash; indeed, it will sometimes be sufficient to use a nitrogen fertilizer alone. The Survey of Fertilizer Practice showed that many farmers use the same sort of mixture for sugar beet as for potatoes, but field experiments leave no doubt that potatoes need more potash than sugar beet. The Survey also showed that farmers manure sugar beet more uniformly than other crops. This must be ascribed to the valuable efforts of the factory agriculturists in collaborating in co-ordinated series of field experiments and in passing on the results to farmers; it indicates the progress that could be made if other crops were studied as carefully and systematically.

It is necessary to recognize the unique position of sugar beet and mangolds in utilizing relatively large quantities of sodium from sodium chloride (agricultural salt). Over a hundred war-time field experiments on sugar beet have shown that a dressing of 3 to 5 cwt. salt per acre gives its own weight of extra sugar. All sugar beet and mangolds should receive such a dressing at any convenient time before sowing, even during a hard spell in winter. Contrary to a common opinion, the sodium in salt acts directly as a plant nutrient for these crops, and not by making soil potassium more available. Salt gives excellent results on sandy soils deficient in potassium, and the extra crops do not make bigger demands on the soil reserves of available potassium. Before the war it was customary to use low-grade potash salt for sugar beet and mangolds, and it was not generally appreciated that the sodium present in this fertilizer was at least as effective as the potassium.

Mangolds. Mangolds do not respond sufficiently well to phosphate to justify the relatively large amounts commonly used, especially on dunged land. Until the 1944-45 season, mangolds were not recognized as a potash-priority crop, but, since supplies became easier, it pays to give mangolds adequate dressings of both sodium and potassium, either as salt and muriate of potash or as low-grade potash salt.

Swedes. Phosphates are needed to start the crop off rapidly, especially on acid soils in wet areas. Dressings of nitrogen should be kept down to the equivalent of 1 or 2 cwts. sulphate of ammonia per acre, especially in the north and west, where larger amounts may render the crop more sensitive to frost damage and mildew.

Other Crops. Experimental work is far less well developed for most other crops, but a few results from recent experiments may be briefly summarised.

Beans and peas are commonly grown without farmyard manure or fertilizer. In the Survey about 40% of the beans received a good dressing of phosphate, but it would be better to use more farmyard manure and potash.

Kale is commonly manured in much the same way as mangolds, but much heavier dressings of nitrogen could be used with advantage.

Flax was treated as a potash-priority crop in war-time rationing, largely on the strength of earlier field experiments in Ireland. War-time experiments in Great Britain showed, however, that flax makes only very modest demands on the soil. Whether grown for fibre or linseed, it should be manured in much the same way as barley, phosphate and potash being given only on acutely deficient soils.

The general levels of manuring indicated from the average results of experiments naturally need considerable modification according to local climate, soils and general farm management.

Effects of Climatic Conditions.

The moist regions of the North and West favour vegetative growth and later ripening, and the effective growing season may be shorter. It is therefore necessary to secure a rapid start and early maturity by using more phosphate, and to restrict the nitrogen. In addition, high rainfall and drainage rapidly wash calcium out of the soils, which become markedly acid. This makes their phosphates less available to crops, and cuts down the residual value of added phosphate fertilizers.

In moist districts 1 cwt. sulphate of ammonia per acre may be taken as a common dressing for cereals and swedes. In very wet areas, *e.g.* in Northern Ireland, the nitrogen for potatoes should be kept down to 1 to 2 cwts. sulphate of ammonia per acre, as heavy top growth may allow blight to spread more rapidly and also delay ripening. The Survey showed that the Western counties of England used about half as much nitrogen for cereals, potatoes and swedes as the Eastern ones, but nearly the same rates for

sugar beet and mangolds, for which there is less objection to heavy growth of tops.

In the recorded experiments summarised in Tables 6 and 7 the average responses to phosphate fertilizers in the South and East of England were about two-thirds, and those in the West of England, Wales and Scotland about five-thirds of those for Central and Northern England. The "most profitable dressings" have therefore to be reduced by 0·2 cwts. P_2O_5 per acre for the drier regions and increased by 0·3 cwts. for the wetter ones. These regional differences were met in the earlier stages of the rationing scheme by allotting phosphates at higher rates to the wetter areas, and later by special allocations for all crops on soils known to be deficient in available phosphate.

The great importance of phosphates was well recognized in Scotland, Northern Ireland and in those parts of England where farming continued throughout the war on the same pattern as before, the extra tillage crops being obtained by shortening the leys. In some of the permanent grassland areas of the wetter parts of England, however, the value of phosphate was not properly appreciated, except perhaps for swedes. The Survey showed that average dressings for cereals were much the same as in the drier East, and for potatoes even less. Many of the newcomers to arable farming were not sufficiently "fertilizer-conscious," and failed to take up their permitted quantities.

Field experiments indicated higher responses to potassium fertilizers in the wetter areas, but the differences were scarcely sufficient to require separate regional groupings within Great Britain. In Ireland experiments on swedes, mangolds, potatoes, oats and flax showed on the average 50% larger responses to unit potash than in Great Britain.

Farmyard Manure and Fertilizer Requirements.

As the amount of farmyard manure available for arable crops on a farm is intimately bound up with the whole system of farming adopted, it is particularly difficult to analyse the part it plays in maintaining soil fertility and feeding crops. At this stage it will be sufficient to consider how to adjust the use of fertilizers to obtain the fullest benefit from whatever amount of farmyard manure can be produced by the current system of management.

Unfortunately far too few good experiments have been carried out to test different combinations of dung and fertilizers, but a survey of the data available brings out some points at variance with common practice. Table 9 gives the average responses of

TABLE 9.

AVERAGE CROP RESPONSES TO 10 TONS OF DUNG PER ACRE FROM BRITISH EXPERIMENTS.

Differences in yield	tons of roots per acre		
	Potatoes	Mangolds	Swedes
Dung *minus* no manure	2·8	7·7	6·4
Dung and fertilizers *minus* fertilizers alone	1·4	2·7	2·6

TABLE 10.

AVERAGE OVERALL RATES OF DUNG IN TONS PER ACRE AND FERTILIZERS AS CWTS. PLANT FOODS PER ACRE USED ON FARMS IN EASTERN (E.) AND WESTERN (W.) COUNTIES OF ENGLAND.

	Dung		N		P_2O_5		K_2O	
	E.	W.	E.	W.	E.	W.	E.	W.
Wheat	1·8	0·9	·19	·10	·16	·21	·00	·00
Potatoes ..	7·4	8·6	·57	·29	·76	·51	·52	·26
Sugar Beet ..	4·2	9·6	·50	·46	·56	·58	·35	·21
Mangolds ..	7·1	12·1	·30	·26	·36	·45	·09	·06
Swedes	3·9	7·4	·27	·11	·33	·63	·04	·04

three root crops to dressings of farmyard manure, and Table 10 shows how farmers in the counties so far surveyed in the East and the West allotted their dung to different crops, and what supplementary fertilizers they employed. The Eastern farmers had, on the average, only 1 to 2 tons of dung per arable acre, whereas in some of the Western counties they had over 10 tons, and could still continue to give dung to a third of their grassland every year. The results of the experiments in Table 9 show dung to be more profitable on potatoes than on mangolds and swedes, as is recognized in the Eastern counties, where, on the whole, potatoes receive more dung than other root crops, especially sugar beet and swedes. For some reason the great importance of dung for potatoes, both for its physical effects and as a source of nutrients, does not appear to have been appreciated in the West, where it is still customary to use more on sugar beet and much more on mangolds.

Analyses of large numbers of samples show that on the average 10 tons of dung contain about 1·0 cwt. nitrogen, 0·5 cwt. phosphoric acid and 1·0 cwt. potash, but it would be quite misleading to regard a 10 ton dressing of dung as equivalent to fertilizers supplying these amounts of plant food, or, as is sometimes done in farm-accounting, to value the dung by the cost of these amounts of plant food in fertilizers. Most of the nitrogen in dung is so firmly locked up in organic forms that it does not become available to crops;

some of it is inevitably lost either as gas or in drainage. The phosphate and potash are less available than those in fertilizers. Systematic comparisons of farmyard manure against fertilizers over several normal crop rotations appear to have been made only in Denmark, and there the aggregate yields from farmyard manure and liquid manure, given at suitable stages in the rotation, were about the same as where half as much nitrogen, phosphoric acid and potash were given as fertilizers.

By comparing field experiments with and without farmyard manure, Crowther and Yates found that on dunged land phosphate fertilizers gave about *one-half*, and potash fertilizers about *one-third* of the crop increases obtained on undunged land. (The figure for potash has been revised since their original paper.) This finding implies that fertilizer dressings should be reduced by about 0·4 cwt. P_2O_5 and 0·6 cwt. K_2O per acre to allow for the amounts of these plant foods furnished by an average dressing of 10 tons farmyard manure per acre. These allowances for the phosphoric acid and potash in farmyard manure should always be borne in mind in drawing up manurial programmes.

In the past it was commonly assumed that farmyard manure reduced the need for nitrogen fertilizers, but field experiments do not support this assumption, the average responses being only slightly less on dunged land. In practice there is no need to cut down nitrogen fertilizers where farmyard manure is used, even though good farmyard manure supplies appreciable amounts of available nitrogen. To explain this result, it must be remembered that farmyard manure supplies other plant foods and improves the physical condition of the land, thus giving better crops, capable of responding to larger aggregate amounts of each of the plant foods, and especially of nitrogen. Moreover, dung is normally applied at a stage in the rotation where the land is most exhausted and most responsive to additional plant foods.

The practical recommendation for using dung and fertilizers to best advantage is to give the dunged fields fertilizers with less phosphate and potash but the same nitrogen. Thus, sugar beet and mangolds on land in good heart might receive only a nitrogen fertilizer where dung is used, but would need roughly equal amounts of nitrogen, phosphoric acid and potash where no dung was available, salt being given in both cases.

Oddly enough farmers in many regions do not appear to appreciate the value of farmyard manure as a source of phosphate and potash. The Survey showed that they generally make very little difference in the choice of fertilizers for dunged and undunged crops, merely

reducing the over-all rates very slightly, but retaining the same proportions between the plant foods. There have been many experiments in which potash gave several tons of extra potatoes on undunged plots, and little or no increase on dunged ones. Farmers could get far better returns from their outlay on potash by cutting down the dressings on the dunged fields, and using more on the undunged fields.

FERTILIZER REQUIREMENTS OF INDIVIDUAL SOILS AND FIELDS.

The results of experiments and surveys so far considered were averages from large numbers, and the conclusions derived from them necessarily refer to average soils. Individual soils vary very widely in their contents of available nutrients, and the range of variation from district to district and from field to field on the same farm was greatly increased by the ploughing-up campaign: Extreme soils, very heavy or very light and dry, were pressed into cultivation ; waste and derelict lands were reclaimed. Many of these soils were so acutely deficient in one or other plant food, that all the work put into them would have been wasted unless the outstanding deficiency was first made good. Difficulties of this kind were particularly frequent in the wetter areas where the ploughing-up campaign led to systems of cropping with which local farmers had little previous experience.

Ploughed-out Grassland and Phosphate Deficiency.

Some widespread deficiencies of lime, and phosphate remained uncorrected because farmers misunderstood the frequent references to mobilising " stored-up fertility " by ploughing out old grass. They tended to identify humus with fertility without realising that, although under grass nitrogenous organic matter builds up, lime and available phosphates are steadily lost. Old arable land generally receives sufficient lime and phosphate to grow crops, but old grassland rarely receives enough to make good the inevitable losses, and so becomes deficient in these important elements of fertility, even though it gains in humus.

The general failure to recognize the needs of ploughed-out grass was clearly brought out in the Survey of Fertilizer Practice. Old arable fields received more lime than newly ploughed-out ones. In all farms surveyed in 1942 only one in every three ploughed-out fields had phosphate fertilizers for cereals, and in half the counties the average rate of dressing with phosphate was actually less on the newly ploughed-out fields than on the old arable. In some counties, *e.g.* Gloucester and Wiltshire, even the root crops on half of the new arable land were grown without phosphate fertilizer or

farmyard manure, probably by farmers with little or no previous experience of arable crops and fertilizers. On such farms many crop failures, commonly ascribed to wireworms, bad cultivations or the utter unsuitability of the land, could probably have been avoided by a little phosphate. Sometimes even County Committees neglected the difference between new and old land, as when they allocated phosphates to farmers in the 1942-43 rationing scheme on a flat rate per acre. The Survey of Fertilizer Practice supplied important evidence for the change-over in 1943-44 to a uniform national scheme, which made special allocations both for ploughed-out land and for soils with acute phosphate-deficiencies.

Potassium Deficiency.

On some areas of light sands or shallow soils, especially those derived from the Upper Chalk in the Southern Counties, there is a general deficiency of potassium, especially on newly ploughed downland; deficient areas are also scattered irregularly throughout the country. They are particularly common on dairy farms, because the potassium in frequent hay crops is lost down the drains in the urine from cowsheds. Acute potassium deficiency makes it impossible to grow potatoes or to establish seeds without potassium fertilizers, and even cereals may fail or give indifferent crops. Moderate potassium deficiencies occur widely and potassium fertilizers should be used more generally, especially in seeding down or renovating leys.

Diagnosis of Mineral Deficiencies.

It is most important to recognize and correct acute nutrient deficiencies. Where crops fail or are stunted or discoloured, farmers should hasten to get advice, if they are unable themselves to discover what is wrong. Great progress has been made in recent years in diagnosing mineral deficiencies, and in distinguishing those due to lack of major plant nutrients from the less common but often more perplexing ones due to deficiencies of elements normally present in crops in smaller proportions, sometimes only in traces. Some of the symptoms are already well known. Lack of nitrogen produces small light-coloured thin leaves; lack of phosphate stunted purplish cereals and crucifers and tall spindly potato tops with upturned leaves of dull colour; lack of potash causes various forms of "leaf scorch," which in potatoes is preceded by bronzing and followed by premature defoliation. Lack of available manganese causes "grey speck" in oats, "speckled yellows" in sugar beet and gives rise to characteristic dark brown spots along the veins of potato leaves. Boron deficiency is

responsible for " heart rot " in beet and swedes, and hollow stems of many crucifers. This deficiency is extremely seasonal, being worse when a dry spell follows one of active growth. Both manganese and boron deficiencies are particularly liable to occur on overlimed soils. Manganese deficiency is usually associated with abundant soil organic matter, and frequently with a high water table.

Suspected deficiencies can often be confirmed by a rapid recovery after a dilute solution of a salt of the missing element has been watered on to the leaves. Manganese deficiencies in potatoes may be treated by including manganese sulphate in sprays or dusts used against blight. On some of the heavier soils spraying the growing crop is preferable to mixing manganese salts with fertilizers, because manganese is soon converted into a useless form in the soil. In areas prone to boron deficiency, 20 lbs. or so of borax per acre may be included with the fertilizers for swedes, sugar beet, mangolds and certain vegetable crops, but there is a risk in using borax generally in fertilizers, because other crops, notably potatoes, might be damaged.

Mineral deficiencies call for expert advice in diagnosis and treatment. The specialist has greater experience in interpreting the symptoms and can check his diagnosis by chemical tests on the leaves, or by injecting or watering-on suitable salts. For a general account of the whole subject reference should be made to Professor T. Wallace's book, " The Diagnosis of Mineral Deficiencies in Plants—A Colour Atlas and Guide," published by H.M. Stationery Office.

Soil Analysis.

Apart from deficiencies causing crop failure or abnormal foliage, there are many less acute stages in which yields may suffer. Analyses of soils or crops, or better of both, can detect many of these deficiencies and thus lead to recommendations for sounder manuring. The most important single test is for soil reaction or acidity, which will be considered briefly in the section on liming materials. Various methods are used for detecting deficiencies of phosphate and potassium. The soils are generally extracted with a dilute acid—commonly citric or acetic—and the results are sometimes quoted as percentages of "available P_2O_5 or K_2O."

The analytical results are not to be taken as measuring well-defined fractions of the plant nutrients in the soil, but as more or less conventional figures needing considerable skill and local experience in their interpretation. For this reason some chemists do

not quote their actual analytical data when they report their practical recommendations to farmers. Similarly they do not favour the analysis of odd samples sent in or the issue of simple field kits for farmers to analyse their own soil. The position is quite different when samples are taken by experienced fieldmen either in normal advisory work or in special surveys. The practical value of soil analysis was abundantly confirmed by its success in war-time. Very many crop failures were explained ; far more were prevented by suitable manuring. As has been mentioned, it was possible in the Fertilizer Permit Schemes to allot considerable extra quantities of phosphates and potash to farms and regions known by earlier work to be deficient or found to be so by special analyses. Every farmer should make full use of the facilities for soil analysis afforded by the National Agricultural Advisory Service, especially when he has indifferent crops, takes over a new farm, ploughs out old grass, or makes any drastic change in his system of management.

An illustration of the practical value of current methods is given below in Table 11 by showing the results of series of field experiments on sugar beet grouped according to one commonly used method of soil analysis for phosphorus and potassium. Although the method sometimes failed for individual experiments, the general run of results shows that the responses of fertilizers were higher in the soils indicated by analysis to be deficient in the corresponding plant nutrient.

Such comparisons between results of field experiments and soil analyses provide drastic tests. The analytical methods are constantly under review and may be expected steadily to gain in

TABLE 11.

ANALYSES BY CITRIC ACID METHOD AND FERTILIZER RESPONSES IN SUGAR BEET EXPERIMENTS, 1936 TO 1946.

Soil analysis	Number of experiments	Additional sugar cwts. per acre
P_2O_5 mg. per 100 g. (soils with less than 5% $CaCO_3$)		for superphosphate
4– 18	54	3·7
18– 28	54	1·5
28– 40	54	1·1
41–172	54	0·5
K_2O mg. per 100 g.		for muriate of potash
3– 6	63	4·7
6– 8	61	4·4
8– 11	62	2·0
12– 26	62	0·8

reliability as they are tested against increasing numbers of field experiments, related to the results of soil surveys, and developed through research in soil chemistry and plant physiology.

Balance of Plant Foods and Interactions of Fertilizers.

In most of the field experiments used in building up the averages in Tables 6 and 7, the individual plant foods were tested on plots which had already received the other major plant foods in basal dressings of fertilizers. Thus the effects of phosphate were generally obtained by comparing NPK plots with NK plots. For practical manuring it is important to know how far the effects of one plant nutrient depend on the presence or absence of another. Unfortunately too few experiments have been carried out to answer these questions with any high precision. For potatoes the response to phosphate increases with the amounts of nitrogen or potash supplied, but nitrogen and potash act much more independently. For sugar beet, on the other hand, the response to nitrogen increases with the amount of potash and is little affected by the amount of phosphate. Such results show that the interactions of fertilizers are far more complicated than is commonly supposed by those who emphasize the importance of proper " balance " in mixed fertilizers or compounds.

Although under some conditions added phosphates may slightly reduce the total amount of potassium taken up by crops, many of the effects commonly ascribed to interactions of fertilizers are more safely interpreted by the " Law of Limiting (or Controlling) Factors." If, on a soil capable of supplying very little available potassium, the size of the crop is increased by giving more nitrogen and phosphorus in fertilizers, the plants will have less potassium per unit weight and will therefore show more acute symptoms of potassium deficiency. Thus, it is commonly observed in field trials that the tops of potatoes on plots with sulphate of ammonia and superphosphate scorch more severely and die down earlier than those left unmanured, even though the final yields may be improved. To raise the supply of one plant food automatically increases the potential response to a second, but it would be misleading to say that increasing the first one caused the deficiency of the second. The farmer's objective should be to discover the peculiar needs of his own fields, and then to adjust the manuring of all his crops by giving a little more of this or less of that, until he balances the nutrient status of his soil for the general system of husbandry he is following. He should realise that mixed fertilizers and purchased compounds owe their popularity to their convenience and to the

way in which they cover the risk of unsuspected shortages on individual fields and farms, and not to any special virtue in the actual "balance of plant foods."

Rate of Action and Residual Value of Fertilizers.

In general the soil should be regarded as a poor storehouse for plant nutrients, and the aim should be to use fertilizers in the best possible way to ensure immediate returns. Acute deficiencies of calcium must be corrected by heavy dressings of liming materials, but those of phosphate and potash are best met by using appropriate fertilizers over a term of years, giving most, if not all, crops at least a little, instead of trying to put matters right by a single heavy dressing, and then expecting it to last through the rotation. The modern tendency in manuring is towards "little and often." This is justified on theoretical grounds and rendered increasingly easy in practice by the development of granular and more concentrated fertilizers, suitable for application in combined fertilizer-seed drills.

Nitrogen Fertilizers.

Soluble nitrogen fertilizers have little direct residual effect in our wet climate, except in dry years on heavy soils; any unused surplus is normally washed out by the winter rains. For this reason it is rarely justifiable to give more than a small amount of nitrogen to autumn-sown cereals, except on very poor soils where a complete fertilizer may aid establishment. The bulk of the nitrogen should be applied in spring, preferably in divided dressings, one early and one late. On heavy soils some of the nitrate built up during a summer fallow may be carried over to benefit the next cereal crop, unless the following winter and summer are too wet. It is for this reason that good cereal crops are obtained on heavy soils in dry seasons. On all soils nitrogen fertilizers have the indirect residual effect that, by increasing the amounts of fodder crops and straw, they also raise the quantity and value of the farmyard manure produced. Rapidly growing market-garden crops, especially when they have to stand the winter, must have large supplies of available nitrogen, and they therefore need repeated dressings of soluble fertilizers or heavy initial dressings of more slowly acting organic fertilizers.

Nitrogen fertilizers are sometimes said to exhaust the soil or "to draw the land." Certainly bigger crops take more out of the land, but farmers do not object to good weather, good seeds or good cultivation because they too give bigger and more exhausting crops. All the major plant nutrients must be supplied at some stage in the crop rotation to maintain soil fertility, but there are many conditions in which it is sound practice to use large amounts of nitrogen

for the less exacting crops, *e.g.* cereals, and leave the soil to provide the other plant nutrients from its reserves or manurial residues.

Phosphate Fertilizers.

Phosphates added to the soil are not washed out, but they may soon go over into quite useless forms. It rarely happens that more than one-quarter of the phosphorus added in fertilizers is taken up by subsequent crops; the remainder is lost within the soil. On acid soils it probably forms unavailable iron phosphates; one of the most important indirect effects of liming very acid soils is to prevent this very rapid wastage of added phosphate. On calcareous soils it reverts to an inert apatite, somewhat akin to that in rock phosphates.

The practical remedy on phosphate-deficient soils is to use phosphate fertilizers frequently in modest dressings applied so as to obtain the maximum immediate effect.

Potassium Fertilizers.

Potassium is washed out to an appreciable extent only from very light or very shallow soils. On heavier soils and perhaps on highly organic soils losses occur in a different way, the potassium passing over into inert and unavailable forms. Although the wastage of potassium is less serious than that of phosphate, less than half the potassium added as fertilizers or in farmyard manure finds its way into crops.

Tenant Right Valuation.

The varying powers of soils to retain added nutrients in useful forms introduces serious difficulties into the problem of assessing the value of tenant-right compensation for unexhausted manurial values of purchased fertilizers and feeding stuffs. Fertilizers applied directly to a crop, especially when they are placed near the seed or sets, are likely to be more effective than residues dispersed throughout the mass of soil by ploughing and cultivation. The plant nutrients in farmyard manure, especially nitrogen, have much lower availability than those in fertilizers. Long-term experiments to assess residual manurial values under a variety of conditions of soil and farming systems are difficult to plan and laborious to conduct, but the results* of the few experiments already undertaken suggest that the old Voelcker & Hall Tables overestimated " the value to the incoming tenant." Against this

* E. M. Crowther "The Residual Manurial Value of Fertilizers and Feeding Stuffs." *J. Royal Agric. Soc. England.* 1946, 107, 107-121.

must be placed the fact that good farmers commonly buy large amounts of raw materials and use them well. A fair measure of rough justice may be attained if an experienced agricultural valuer balances the commercial and scientific considerations by adapting certain general and agreed rules to the special circumstances of the individual farm concerned.

Guidance for valuers has recently been supplied in the unanimous Report of a Conference appointed by the Ministry of Agriculture. This report, unlike the previous ones, has been accepted by the representative organisations interested. Its main recommendations are summarised in Appendix B.

Placement of Fertilizers.

There is a disturbing contrast in technical efficiency between the chemical engineering equipment required to produce modern fertilizers and the primitive machines used to apply them in the field. In the old days the farmer himself spread fertilizers by hand over his seedbeds, and most drills are still intended to broadcast evenly. In a few restricted parts of England superphosphate has long been drilled down the same spouts as the cereals, and this method has become universal in dry countries, where vast acreages have to be sown in a few days. In South and Western Australia to drill ½ to ¾ cwt. of ordinary superphosphate per acre with the seed commonly makes the difference between success and failure in establishing a cereal crop before the top few inches of soil dry out.

Machines of types developed for this purpose in the United States, Australia and New Zealand proved very popular during the war. The numbers in England and Wales reached 7,000 by 1942 and 20,000 by 1948. It has been found in practice and confirmed in trials by research institutes and County Committees that phosphate fertilizers drilled with cereals are far more efficient than the same amounts broadcast, 1½ cwts. of superphosphate combine-drilled being on the average as good as 3 cwts. broadcast. This points the way to an obvious economy.

Great progress has been made in the United States in the development of special fertilizer placement drills for row crops, largely as the result of sustained investigations and experiments over 20 years by the U.S. Department of Agriculture and a joint committee representing the manufacturers of fertilizers and farm machinery, and the research and advisory services. Conditions in the United States provided obvious opportunities to a machine-conscious people. The principal heavily manured crops—cotton and maize—are grown in rows one yard apart, and, to allow the use of standardised machinery, potatoes and many vegetable crops are grown

at the same spacing. Fertilizers broadcast between such wide rows would be dispersed through an unnecessary bulk of soil and remain inoperative until the crop roots were well established, when it would be too late for their full effects. To drill compounds down the same spouts as the seeds would produce too heavy local concentrations of soluble salts close to the seeds, ammonium and potassium salts being particularly apt to check germination. The current recommendation is to place the fertilizer in bands an inch or so below the seed and about two inches to one or both sides of the line of seeds or cut potato sets. A wide variety of combined fertilizer-seed drills or planters has been designed to secure this distribution.

Field experiments in Britain have shown that it makes little difference how the fertilizers are applied to potatoes, provided the land has already been ridged in preparation for planting. Broadcasting over the ridges is just as good as placement in bands in contact with or below the sets or below and well to the side of the sets. All these methods secure the advantages of controlled placement close to the sets, but broadcasting before ridging is far less efficient. The discrepancy between American and British results illustrates the danger of importing new techniques without proper tests under local conditions. The benefits from fertilizer placement in the American experiments were obtained mainly with cut sets planted mechanically on flat land, conditions rarely employed in Britain.

Gains from controlled placement have also been obtained in Britain on other crops, but many seeds are far more sensitive than cereals to damage by the soluble salts in fertilizers placed close to the seeds. Banded application of fertilizers cannot yet be recommended generally; the conditions for safety must be firmly established and the drills made more accurate and reliable.

Alternative Forms of Straight Fertilizers.

Farmers generally need to use both "straight" fertilizers, which supply only one of the principal plant nutrients, and mixtures made on the farm or purchased as so-called "compound fertilizers," containing two or more plant nutrients. Most of the straight fertilizers are highly standardised products, but it is necessary to know something of their special properties to make the best use of them.

The relative costs of comparable straight fertilizers are obtained by dividing the price per ton by the percentage of either N, P_2O_5 or K_2O to obtain the cost of 0·01 ton or 0·2 cwt. of plant food.

This is known as the " unit price." Thus, for sulphate of ammonia with 21% N at £10 per ton, the unit price is 200/21 shillings or 9/6. It will be shown in the next section how unit prices can be used to estimate the relative costs of home-made mixtures and purchased compounds. Typical analyses and prices for both " straights " and " compounds " are given for reference in Appendix A. Except for potash fertilizers and basic slag, prices are reduced for early delivery.

Nitrogen Fertilizers.

By far the most important nitrogen fertilizer is sulphate of ammonia. Care is needed to spread sulphate of ammonia carefully, especially at heavy rates, for vegetables and other green crops. Irregular distribution may produce dangerous local excesses and check young plants or damage established ones. For this reason many market growers prefer to use the safer but much more expensive organic forms, though it would often pay them to learn how to use repeated small dressings of sulphate of ammonia instead. For farm crops there is little danger. Sulphate of ammonia increases the loss of lime from the soil, but the effect is fairly small (about one-third of the weight of sulphate of ammonia) and is easily put right by regular liming. Sulphate of ammonia is particularly useful for shallow-rooted crops in wet districts, and especially for potatoes and oats.

Ammonium nitrate, another synthetic form, is produced on a large scale for explosives. It has the inherent disadvantage of taking up moisture from the air. If this can be overcome by waterproofing the granules or in some other way, the existing plants could produce a useful fertilizer. One process, which can be employed only at the largest works, is to granulate the ammonium nitrate with calcium carbonate, to give the well-known proprietary product " Nitrochalk."

Synthetic ammonia is used to prepare ammonium phosphate, which is sold as such or in concentrated compound fertilizers.

The nitrate of soda used in this country is a refined natural salt imported from Chile, but on the Continent a synthetic form has been made on a small scale. Nitrate of soda acts very rapidly and is valuable as a top dressing, especially for green crops and for cereals checked by cold weather or wireworms. It is readily washed into the subsoil and is therefore especially useful for deeply-rooted crops in dry districts, but not for lighter soils in wet areas. For mangolds and sugar beet it has the additional advantage of furnishing sodium, a plant nutrient for these, but for few other, crops. Apart from the special cases mentioned, there is little to

choose between nitrate of soda and sulphate of ammonia at current market prices: unit nitrate is commonly better than unit ammonia to an extent which just about pays the extra cost of 38 per cent. A potassic Chile nitrate, strictly speaking a compound fertilizer, is useful for market gardens, especially for cauliflowers, but is too expensive for farm use.

Among animal wastes the proteins in muscle, blood, hoof, horn, and wool form active nitrogen fertilizers. The popular demand is so great relative to supply that they are very much more expensive than the inorganic forms. Their main merit is that they contain no soluble ammonium salts, and so may be applied safely, even by workmen with large hands. Soil bacteria rapidly split off ammonia from these proteins, and very fine forms, such as dried blood, act nearly as quickly as soluble inorganic salts. The speed of action of hoof-and-horn meal depends on the size and shape of the ground material, the larger lumps providing little pockets from which roots can take up ammonia or nitrate liberated more or less in accord with the steadily increasing needs of growing crops. The value of shoddy depends on its content of wool, as shown by the percentage of nitrogen.

Other organic wastes should only be purchased after technical advice. Those who seek special virtues in organic materials as such should be warned that some organic wastes have very little fertilizer action. Thus, the proteins of leather are so changed by the tanning process that they decompose far too slowly to be of much use to crops, as may be seen from the time it takes for an old boot to rot away. The so-called treated leather meals at present on the market are little more active. The small amount of waste chamois leather produced from the manufacture of gloves is an exception: it is an active fertilizer because the tanning is done by oil in place of vegetable- or chrome-tans. A rough working rule for assessing the immediate fertilizer value of most plant and animal wastes is to assume that the first 3% of nitrogen of the organic matter is almost useless. This rule cuts out a number of low grade organic wastes occasionally offered.

Phosphate Fertilizers.

Apart from bones and basic slag, all phosphate fertilizers are prepared from imported rock phosphates, which are closely related in chemical composition and structure to the mineral " fluorapatite " $Ca_{10}(PO_4)_6F_2$. There are, however, great differences in agricultural value between rock phosphates. The coarsely crystalline types, sometimes termed " crystalline apatites ", which were formed from molten magmas, have very little value for direct applications to

the land. Examples are the " Kola concentrate " imported from Murmansk during the war and the Tororo phosphate now under test in Uganda. The bulk of the rock phosphates used either directly on the land or as raw materials for making soluble phosphate fertilizers were formed at ordinary temperatures, either in sea water or from solutions percolating into limestone. These sedimentary phosphates, known on the continent as " phosphorites," are sometimes described as amorphous, because they do not show clear-cut crystalline characters under the microscope. Their properties are determined by the submicroscopic size of their ultimate crystal units and the presence of various impurities. The soft earthy forms from North Africa are more suitable for direct application to the land than harder forms such as Florida pebble or Nauru. When the North African supplies were cut off during the war a search was made for alternatives. A rock phosphate from Curacao proved useful for direct application even though it was hard to grind ; it differed from the usual kinds of rock phosphate in having much less fluorine. Bones resemble rock phosphates in having an apatite structure ; the phosphate is present as hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$.

All these apatite-like materials provide little or no phosphate in forms available to plants until they are broken down by acids or by certain high-temperature processes. Breakdown by acid occurs naturally in acid soils, and it is well known that suitable rock phosphates, when finely ground, provide very useful fertilizers on acid soils in wet areas, especially for swedes and grassland. Bone phosphates are attacked in the same way. Neither ground rock phosphate nor bone products should be used on basic soils or on recently limed land.

For more general use the rock phosphates are broken down by sulphuric acid in the century-old process of making superphosphate, by phosphoric acid in the newer process for making triple superphosphate or by various high-temperature processes. In superphosphate, triple superphosphate and ammonium phosphate, the phosphate is present in a water-soluble form. When these materials are used as fertilizers the soluble phosphate soon reacts with calcium from the soil to form a dicalcium phosphate which is only slightly soluble in water. The added phosphate is not washed out of the soil but is spread in a thin film over the soil particles and remains available to plants for a period which depends on the general character of the soil. In very acid soils the added phosphate may be taken up by the clay colloids or pass over to a very inert iron phosphate ; in calcareous soils less active materials resembling apatite may be formed ; in neutral or slightly acid soil some of the phosphate may

remain available for years. The conversion of soluble phosphates into more inert forms, often termed " phosphate fixation," presents some of the most difficult problems in soil chemistry and in the efficient use of phosphate fertilizers.

Rock phosphates may also be decomposed at high temperatures. One process gives elementary phosphorus which can be burnt to phosphoric oxide. With water this gives phosphoric acid which can be used to make triple superphosphate. If the burning is done in contact with rock phosphate and in the absence of water, the product is " calcium metaphosphate " (62% P_2O_5), a very concentrated and slowly acting fertilizer used in the United States for establishing leys and cover crops. Another process was developed in England during the war as a possible means in economising in sulphuric acid, had supplies of imported pyrites been cut off. Rock phosphate was sintered with soda ash in a rotating furnace and the fluorine driven off by steam. The produce, " Silico phosphate ", gave good results in field trials, especially for swedes on acid soils.* A novel American process drives off the fluorine at still higher temperatures and yields a " fused tricalcium phosphate " which is insoluble in water but readily available to plants ; it is sufficiently free from fluorine to be a useful mineral supplement for feeding to animals.

Dicalcium phosphate can be prepared by adding basic materials to soluble phosphates but not by adding restricted amounts of acid to rock phosphate. Although it is only slightly soluble in water it is readily available to plants. As will have been seen, the water-solubility test is of little use in valuing the more modern forms of phosphate fertilizer.

There is no clear evidence that tricalcium phosphate, $Ca_3P_2O_8$, which featured so prominently in the older textbooks and fertilizer analyses, plays any part in the chemistry of soils and fertilizers, except as the high-temperature product already mentioned.

Basic slag, being a relatively inexpensive by-product from steel making, must be accepted as it comes, but buyers should distinguish carefully between the various kinds. High pressure on steel-making introduced some changes at the works, and, in addition, it was necessary to grind low-grade slags, *i.e.* those with low total contents of phosphoric acid. Although prices follow grades, it will be noted from Appendix Table A that low-grade slags are more expensive per unit of phosphoric acid (*i.e.* 0·01 ton of P_2O_5). Unfortunately there is a further complication not covered by the

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* For further particulars and results of field experiments, see E. M. Crowther and F. M. Lea, *J. Min. Agric.* 1946, Vol. 53, pp. 102-105.

price schedules. The greater part of the basic slag produced, whatever the grade, contains phosphates which break down rapidly in moist soil or acid solutions to liberate soluble phosphate, which behaves in the soil in much the same way as that in superphosphate. There is, however, another class of basic slag from works using fluorspar in the Open-Hearth process of making steel, in which the phosphate is present as crystals of very inert fluorapatite. It is important not to confuse these two kinds of basic slag. The best index of the value of all basic slags as phosphate fertilizers is given by the percentage of " citric-soluble phosphoric acid " which, by direction of the Fertiliser Control, is given on all invoices. Low-soluble and low-grade basic slags should be used as liming materials supplying some phosphate, and for this purpose they have proved popular where they can be obtained very cheaply near the works.

Potassium Fertilizers.

The range of potassium fertilizers is much narrower, and the problems correspondingly easier. Apart from relatively small amounts of special blast furnace dusts and vegetable ash, which remained outside the Fertilizer Permit Scheme, all potassium fertilizers are salts prepared from past or present inland seas. Till 1939 our supplies came almost entirely from a belt of deposits running across France, Germany and Poland. They were mainly mixtures of chlorides of potassium and sodium, and were standardised to provide the equivalent of 14, 20, 30 or 50% K_2O. Through some odd and unexplained commercial convention, Great Britain had none of the 40% grade, the commonest form on the continent. There was also the more expensive sulphate of potash, and the small amounts of a mixed "sulphate of potash-magnesia."

When these sources were cut off, limited supplies were obtained from the Dead Sea, Spain and U.S.S.R. in a standard grade of muriate of potash with the equivalent of 60% K_2O.

When European supplies were restored after the war a large proportion of the imports were in the grade with 40% K_2O.

Sulphate of potash will always remain a good deal more expensive than muriate of potash, because it needs more elaborate processing. The sulphate will be preferred for tomatoes and other crops under glass, and for heavily manured field and garden crops, especially fruit, vegetables and potatoes. In glasshouses and for bush-fruit the accumulation of chlorides might be harmful. For potatoes there is little difference between the sulphate and the 40% and 60% grades of muriate for equivalent amounts used in moderate rates of dressing. The sulphate is preferred for heavy dressings because

large quantities of sodium and chloride reduce the dry matter content of potatoes and may impair the cooking quality. For sugar beet and mangolds the low grades are preferred for the sodium they supply, unless they prove too expensive.

MIXED OR COMPOUND FERTILIZERS.

Since many crops and soils need two or more plant nutrients there is an obvious convenience in supplying them in mixtures, which may either be made on the farm or purchased as prepared "compound fertilizers." Opinions on the relative merits of the two alternatives have often been debated, and general practice has followed opposite courses in different countries. In Germany compound fertilizers were at one time officially discouraged, but more recently new concentrated compounds and ammoniated superphosphate were favoured; propaganda for the separate straight fertilizers had, however, led to unbalanced manuring on many farms. By contrast, in the United States about three-quarters of the total plant foods were purchased as compounds. A single grade with 3%N, 8%P_2O_5, 5%K_2O accounted for nearly one-tenth of the total tonnage of compound fertilizers and the ten leading grades for almost one-half of the total. There was a strong movement towards standardisation before the war, and a number of States laid down by law the analyses of the mixtures to be offered for sale.

In the United Kingdom before the war about half the plant food was purchased as "straights" and half as "compounds," of which there was a bewildering variety. Many farmers bought their compounds mainly on the strength of the manufacturer's name or the merchant's recommendation, paying little attention to the analysis in the warranty under the Fertilisers and Feeding Stuffs Act. Research institutes and advisory services could not test or recommend proprietary mixtures, and generally framed their experiments and advice in terms of plant foods or straight fertilizers. Some farmers had special mixtures made up for them, but it was not generally realised how much unnecessary labour had to be paid for in handling small batches, when many of the mixtures could easily have been prepared, transported and stocked in bulk.

The war greatly accelerated the standardisation of compounds. In Northern Ireland farming was sufficiently uniform to make it possible to have a single compound fertilizer for potatoes and to cover all other requirements by rationing in terms of straight fertilizers. In England and Wales the manufacturers soon pruned their lists of the minor variants. During the 1941-2 season in England and Wales, compounds containing a high proportion of

superphosphate were excluded; compounds with all three plant foods were not to have more P_2O_5 than one-and-a-half times the N or twice the K_2O; for those without potash the water-soluble P_2O_5 was not to exceed twice the N, or the total P_2O_5 three times the N. Somewhat similar restrictions remained in force from 1941 in Scotland, where there was no formal permit scheme.

National Standard Compounds.

The first standard compound, introduced in 1942 to meet the needs of private gardeners and allotment holders for a sound fertilizer containing potash, was the National Growmore Garden Fertilizer, with 7% N, 7% P_2O_5, and 7% K_2O at a price of 25/- per cwt. To facilitate the National Fertilizer Rationing Scheme in 1943-4, three National Compound Fertilizers were introduced at fixed prices, and particulars given to all farmers in the pamphlet issued with their fertilizer permits.

For 1947-8 there were four National Compound Fertilizers with the compositions shown below. (The standard rates of dressing given for illustration are those covered by the fertilizer permits over the period 1944 to 1946).

	% N	% Total P_2O_5	% K_2O	Price per ton March-June 1948 £ s. d.	Standard dressing per acre.
No. 1	7	7	10·5	10 14 6	10 cwts. for potatoes and mangolds
No. 2	9	7·5	4·5	10 8 6	7 cwts. for sugar beet.
No. 3	6	12	—	9 5 6	4 cwt. for other roots
No. 4	4	15	—	9 3 6	3 cwt. for other roots

With these four mixtures and some extra straight fertilizers, farmers can cover all their essential needs with a minimum of trouble and expense. The present series will have to be extended to allow finer adjustments to special requirements, but it is to be hoped that the advantages of standardisation will be maintained.

The standard compounds should not be associated too rigidly with individual crops, for each compound fits a variety of conditions. Thus, after the restrictions were relaxed, National Compound No. 1 could be used not only for potatoes on average land, but for sugar beet and even for cereals on soils acutely deficient in potash.

National Compound No. 3 was suitable for fodder crops on ordinary land and for cereals on phosphate-deficient land.

Relative Costs of "Compounds" and "Straights."

In the long run manufacturers will profit more from a high aggregate turnover of standard compounds than from restricted sales of a few more expensive specialities. Farmers must expect to pay rather more for compounds to cover the cost of the more intimate mixing and the better physical condition which the manufacturer can provide.

The controlled prices of fertilizers from July 1947 are given for reference in Appendix Table A. To compare the prices of compound fertilizers with those of straight fertilizers supplying the same amounts of plant foods the first step is to work out " unit prices " for N from sulphate of ammonia, soluble P_2O_5 from superphosphate, insoluble P_2O_5 from ground rock phosphate and K_2O from muriate of potash. (To allow for carriage from the import stores to the nearest station 15/- per ton should be added to the price of muriate of potash).

		Delivered price per ton	Unit price	
		£ s. d.		
Sulphate of ammonia	20·6% N	10 8 0	N	10/–
Superphosphate	18% P_2O_5	5 19 0	sol. P_2O_5	6/7
Ground rock phosphate	25% P_2O_5	5 6 6	insol. P_2O_5	4/3
Muriate of potash	60% K_2O	14 8 0	K_2O	4/10

The percentages of the plant foods in the compound fertilizer are multiplied by the appropriate unit prices and the products totalled; this gives the cost of equivalent plant foods in the form of straight fertilizers. The extra cost of the compound fertilizers, sometimes called the " basic price," represents the additional cost of processing and selling the compound fertilizers. At the prices fixed from July 1947 compound fertilizers of ordinary strength cost about 48/- per ton and the concentrated ones about 69/- per ton more than equivalent amounts of straight fertilizers. A given quantity of plant foods costs about one-third more if it is bought in ordinary compounds and one-fifth more if it is bought in concentrated compounds than if it was bought as straight fertilizers. In making such comparisons farmers must, of course, allow for the extra cost and trouble of mixing straight fertilizers at the farm.

The fact that the additional or basic price of concentrated fertilizers is less than that of ordinary strength fertilizers supplying equivalent amounts of plant foods illustrates the economy in handling and transporting more concentrated materials. Detailed tables given in the Appendix to the first edition of this pamphlet showed that in 1945 there was a greater divergence between ordinary and concentrated compound fertilizers; the extra costs above the price of equivalent plant foods in straight fertilizers were 35 per cent. for ordinary compounds and 15 per cent. for concentrated ones. The revision of prices in 1947 increased those of concentrated compounds by about 35/- per ton and those of ordinary compounds by only a few shillings per ton.

For working out relative costs of fertilizers it is convenient to note that current unit prices are very close to 10/- for N, 6/8 for P_2O_5 and 5/- for K_2O. It is therefore fairly easy to remember that £1 will buy either 2 units N, 3 units P_2O_5 or 4 units K_2O, or that £100 will buy either 2 tons N, 3 tons P_2O_5 or 4 tons K_2O. From these round figures a rough estimate of the total annual expenditure on fertilizers can be made. Thus for the estimated consumption in the United Kingdom in 1947-8 we have:

	thousand tons.	million £
N ..	186 ..	9·3
P_2O_5 ..	372 ..	12·4
K_2O ..	190 ..	4·8
		26·5
	Add one-sixth	4·4
	Total	30·9

One sixth is added to allow for the extra cost of about one-half of the total bought as compounds and in other forms more expensive than the standard straight fertilizers.

The national annual fertilizer bill is of the order of £30,000,000. In addition there is a state subsidy of £8,300,000.

Bone Fertilizers.

Some organic wastes supply both nitrogen and phosphoric acid, and their costs relative to straight fertilizers may be calculated in the same way as for compounds. Bone products provide slowly available phosphate in acid soils, but not in the alkaline soils produced by heavy and repeated liming. Sometimes market

garden soils have large reserves of bone phosphate (as shown on analysis by acid extraction), but are unable to satisfy the needs of young plants for immediately available phosphate. On such land it would often be informative to test the effect of a little superphosphate on tomatoes, potatoes and other sensitive crops in place of the usual bone manure.

Manuring for Quality in Crops.

Every farmer knows that crops may vary in value according to the conditions under which they are grown, and that a great deal of skill is required to ensure quality as well as quantity. Unfortunately, it is becoming fashionable to discuss "quality" as if it were some transcendental attribute to be attained only by following a prescribed ritual. The word "quality," like most other abstract nouns, should be scrutinised carefully; as applied to a crop, it cannot mean much more than "suited to its purpose."

For crops used in industry, market conventions can be checked and developed by research, and the effects of manuring tested both by buyers' valuations and more objective data. For barley the nitrogen percentage on dry weight is an important factor, and field experiments have shown that neither the price given by skilled valuers nor the nitrogen percentage is appreciably altered by moderate dressings of nitrogen fertilizers, which greatly increase yields. For sugar beet quality depends primarily on sugar percentage, by which prices are fixed in this country, but other factors may also influence the extraction and crystallization of sugar in the factory. Much more experimental work is needed before these factors can be defined and measured sufficiently well to influence sugar beet prices and practical manuring.

For fodder crops, hay and pasture, the principal factors are the proportions of protein, readily digestible carbohydrates, fibre, vitamins and minerals, especially calcium and phosphorus. All these factors can be determined in tests on the effects of fertilizers, and there is abundant evidence to show that quality can often be increased by judicious manuring and management. Adequate lime and phosphates, together with sufficient nitrogen from soil organic matter, leguminous plants or fertilizers are the commonest needs. There are large areas in the United Kingdom and vast regions of the tropics where fodder crops and human foodstuffs are of low nutritive value through lack of available plant nutrients in the soils. Sometimes notable improvements can be made by changing the system of land management, but often the most direct way is to bring in lime and suitable fertilizers. At the present time it is particularly important to improve the nutritive value

of hay by using nitrogen fertilizers, even quite shortly before hay-making, and cutting early.* For market garden crops the obvious requirement is for well-formed produce unchecked by drought, frost or nutrient deficiency. This means maintaining soil moisture and organic matter, keeping down weeds by frequent early cultivation and supplying sufficient plant foods, especially nitrogen. By contrast, good quality sometimes requires starving the plants of nitrogen, as in growing very red dessert apples in grassed orchards.

There is no universal definition of "quality," and no simple formula for obtaining it by manuring. The more romantic compost enthusiasts argue by analogy from the known importance of vitamins in animal nutrition and of hormones in plant and animal physiology, that similar materials ought to be important in feeding plants. Biochemical research progresses rapidly, and it is conceivable that some day we must add certain complex organic molecules to our lists of essential plant nutrients. Cases may possibly be found in which fertilizers and manures affect the vitamin contents of crops. The contemplation of these possibilities and the search for them are, however, very different matters from assuming the results in order to advertise special practices. No critical experiment has yet shown any appreciable difference in vitamin content or nutritive value between crops grown with fertilizers and with farmyard manure.

Organic Matter and Maintenance of Soil Fertility.

Some discussions on soil fertility raise a false antithesis between "natural" and "artificial" manures. There is, of course, no conflict between using bulky organic manures, such as farmyard manure or compost, and using fertilizers. The two classes of material serve different purposes; the best results are obtained by a judicious combination. Bulky organic manures supply useful but highly variable quantities of plant nutrients together with organic materials which may have immediate physical effects on the soil and important secondary ones through increasing the amounts of more fully rotted material, sometimes called "humus." This colloidal group of materials plays an important part in maintaining good soil structure, in holding some plant foods in immediately available forms and in slowly liberating others.

The fluctuating balance between groups of micro-organisms in the soil is necessarily influenced by adding fresh organic materials which rot down. Certain pathogenic organisms may be checked

* See *e.g.* A. W. Ling and E. L. Smith. "An Investigation into the Composition of Hay." *Journal of the Bath and West and Southern Counties Society* Sixth Series, Vol. XIV, 1939-40, pp. 29-60.

or crowded out, and others increased, but the complex inter-relationships have not yet been successfully analysed. Bulky manures, grass roots, dead leaves and crop residues of all sorts supply food for worms, which show by their changing numbers whether the system of land management is raising or lowering the organic matter content of the soil. In much the same way the roots in undisturbed grassland feed wireworms. Most of these biological changes are, however, inevitable by-products of cultivating, manuring or resting the soil, and have little practical bearing on the farmer's choice of organic or inorganic manures. As far as is yet known the principal factors responsible for improving the soil structure of land rested under grass are the mechanical effects of the grass roots and various soil fungi, the gummy materials formed by certain micro-organisms and the colloidal effects of the more resistant organic residues.

Market gardeners may sometimes be able to choose between stable manure and fertilizers, but farmers are restricted to the waste materials produced on the farm or purchased nearby. It is quite impracticable to manufacture the large quantities of compost sometimes recommended for farms. Farmers are even loathe to cart farmyard manure to their more remote fields, and they have not succeeded in organising the exchange of straw for farmyard manure between arable and dairying districts, even where, as in Lancashire, the two are clearly demarcated in a single county. There is little prospect of transporting other low-grade wastes over long distances.

The Use of Straw.

Even among farmers discussions on farmyard manure are too often focussed on the alleged manurial value of the straw. They look wistfully at the increasing stacks of straw, and think how easy it would be to farm their land if they could convert them into farmyard manure in accordance with the old rule that 1 ton of straw equals 4 tons of dung. They forget that the manurial value of farmyard manure comes almost entirely from hay, root crops and other feeding stuffs (often imported), and that even in the old days they used to speak of "growing crops at a loss to feed stock at a loss to produce manure to grow crops ...."

The value of the plant foods in straw is extremely low. A crop of 30 cwts. of straw from an acre of average land may contain about 0·15 cwt. N, 0·06 cwt. P_2O_5 and 0·3 cwt. K_2O, but, if the soil on which it is grown is deficient in available potash, the straw may have only about 0·15 cwt. K_2O per acre. To return this straw to the land would do very little to remedy the potash deficiency.

The value of straw is indirect and mainly physical. It acts as a sponge to retain urine, opens up heavy soils and may improve soil structure. The virtue of balanced farming does not lie in treading straw to manure but in sound rotations, leys alternating with tillage and corn with roots. Animals are needed to make good leys, which in turn build up stable soil crumbs and add nitrogenous organic matter. In the absence of liquid manure tanks, straw provides an essential link in the cycle of fertility by conserving nitrogen and potassium from other foods fed to the stock. This link is particularly weak on dairy farms, which often need more tillage land to grow fodder crops and straw and to utilise the farmyard manure.

Where animals cannot be kept, straw may be returned either directly or as composts prepared with sulphate of ammonia and limestone or with sewage sludge. On heavy farm soils it is often better to plough the straw in during autumn and apply extra nitrogen fertilizer directly to the following crop of potatoes or other roots. Composted straw may be preferable on light land which may dry out too rapidly if opened up by raw straw.

In market gardens all organic waste should be composted or ploughed in directly, both to return nutrients and improve soil structure. Bracken cut in July provides a good bulky manure, rich in nutrients. Sewage sludge supplies available nitrogen and sometimes available phosphate, but it lacks the characteristic physical effects of the fibrous material in partially rotted straw. Some forms of town refuse may occasionally be useful, if the amounts of broken glass, cinders and ash can be kept down, but successful salvage has reduced both the organic matter and plant foods. Finally, a season may be sacrificed to grow green manure crops. The essential point is to grow sufficiently heavy crops, if necessary by manuring, to smother weeds and provide a large bulk of organic matter. Poor green manure crops may be worse than useless. Leguminous green manures may add nitrogen, and all green manures may bring up some nutrients from deeper layers, but the cultivations needed to establish the crops are just as wasteful of soil organic matter as those for crops which can be sold or fed to stock. There is little to be said for green manuring where it is possible to use a sound rotation including leys.

Liming Materials.

Progress has been made in the use of lime and limestone with the subsidy under the Land Fertility Scheme, but vast areas of acid soils still need liming. Supplies are more easily obtained than ever before, and no farmer should be in doubt about which fields

to lime and what rates and form to use, for the National Agricultural Advisory Service can measure soil acidity and recommend suitable dressings with confidence.

Some very acid soils may need several tons of liming material per acre to make a worth-while change, but other soils may require only a ton or two per acre—or none at all. The lime requirement is commonly high on old grassland in wet areas and on heavy soils. It is sound practice to lime the more acid fields sufficiently to bring the whole of the farm within a convenient range and then to maintain this by moderate dressings applied periodically.

One war-time development was the provision of more ground limestone as an alternative to burnt lime, though, unfortunately, the unit price of limestone has remained unduly high. In some parts, especially in the West and North, there is an unjustifiable old prejudice against limestone. Although twice as much is required, it is more easily stored and applied, and it can go on at any time. There is no need to use exceedingly fine material; samples ground to 50 per cent. through the 100 mesh sieve will generally have sufficient fine material for rapid action; the coarse grit makes distribution easier and provides slowly acting reserves.*

In some quarters there is also a prejudice against using dolomitic or magnesian limestone and limes. This may have arisen from unfortunate experiences with heavy dressings of burnt lime long ago, and been strengthened by a Regulation under the Fertilisers and Feeding Stuffs Act that only the oxides, hydroxides and carbonates actually present as calcium compounds should be included in the official warranty. Magnesium oxide is more caustic than calcium oxide, and burnt magnesium lime should not be used in dressings over, say, 2 tons per acre. Up to this rate for burnt limes and at any rate for ground limestones, materials rich in magnesium are at least as effective as high calcium products. They have the additional advantage of supplying available magnesium, which is sometimes deficient, especially in fruit and market garden soils receiving little farmyard manure. There is everything to be said for using magnesium limestones occasionally on acid soils as an alternative to the more usual high-calcium limestones.

There is no need to build up large reserves of free calcium carbonate in the soil. The aim should be to keep the reaction very slightly on the acid side of neutrality by periodic dressings with rather gritty limestone. Sometimes, under very wet conditions,

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* See *e.g.* T. Wallace, "The Utilisation of Local Supplies of Chalk and Limestone for Liming Land." *Journal of the Bath and West and Southern Counties Society*, Sixth Series, Vol. III, 1928-29, pp. 60-70.

it may prove more economic with rotations confined to the more resistant crops to keep soils appreciably more acid. The rate of loss of lime depends on soil texture and the total amount of active or exchangeable lime present; much smaller regular dressings are needed to hold soils at moderate acidity than to keep them neutral.

On light soils care should be taken to avoid over-liming, as this may induce deficiencies of boron or manganese by reducing the availability of these elements in the soil. The risk of damage from excess should not, however, discourage farmers from liming really acid soils, and especially those ploughed out of poor grass or waste land during the war. Some of these were so acutely acid that even such resistant crops as potatoes have failed through lack of lime.

Consumption of Fertilizers and Liming Materials 1939 to 1948.

The Ministry of Agriculture has very kindly supplied data for the total consumption of fertilizers and liming materials for each of the years since 1939. These are given in Table 12 with the acreage figures for crops and grass to summarise the course of the ploughing-up campaign and the rapid expansion in the use of fertilizers. From 1939 to the peak production year of 1944 the amount of nitrogen used had trebled, the amount of phosphoric acid had doubled and, in spite of all supply difficulties, the amount of potash had increased by one-half. Even when allowance is made for the greatly increased acreage of arable land, the rate of dressing per arable acre had doubled for nitrogen, increased by one-half for phosphate and been maintained after 1944 for potash. These figures record notable achievements but they leave no room for complacency. Even if all the fertilizer went on arable land the average dressings per acre during the last few years amounted only to about 1 cwt. sulphate of ammonia, 2 cwts. superphosphate and 0·25 cwt. muriate of potash or say 2·5 cwt. of a compound fertilizer. During the war no phosphate or potassium fertilizers were allowed to be used on grassland, and even before the war little of the grassland received any systematic manuring. The urgent need for better hay and more silage and dried grass calls for much heavier and more general manuring of grass. If the war-time rates of manuring arable land are to be kept up and if grassland is to play its proper part in the Agricultural Expansion Programme, it appears inevitable that the consumption of fertilizers must continue to increase. It seems impossible to attain the needed output from average rates of manuring represented by the steady fertilizer consumptions from 1944 till 1947. It must be remembered

too that the distribution of fertilizers between farms has become less uniform since the Fertilizer Permit Scheme was withdrawn. Some farmers on good land are using more fertilizer than during the war, but many farmers on poor soil are using much less. The

TABLE 12.

CONSUMPTION OF FERTILIZERS AND LIMING MATERIALS IN THE UNITED KINGDOM, AND AREAS OF CROPS AND GRASS.

(Tillage land = crops + fallow. Arable land = tillage + temporary grass. Fertilizers for year ending June 30th. Liming materials for year ending May 31st. Crop acreages for June 4th. 1947-8 figures are estimates).

	Fertilizers			Liming Materials		CaO	CaO
	thousand tons of			million tons of		Mean %	cwt. per
	N	P_2O_5	K_2O	product	CaO	product	arable acre
1939	60	170	75	1·74	1·30	75	2·0
1940	77	196	85	1·33	1·00	75	1·4
1941	128	233	47	1·49	1·06	71	1·3
1942	168	287	62	1·82	1·26	69	1·4
1943	171	303	73	4·10	1·76	43	1·9
1944	182	344	113	4·64	2·04	44	2·1
1945	172	346	116	3·27	1·86	57	1·9
1946	165	359	123	3·42	1·96	57	2·1
1947	164	355	121	2·73	1·51	55	1·6
1948	186	372	190	4·50	2·31	51	—

Average Fertilizer Dressings				Tillage	Leys	Arable	Permanent Grass
	as cwts. per arable acre				million acres		
	N	P_2O_5	K_2O				
1939	0·09	0·26	0·12	8·8	4·1	12·9	18·8
1940	0·11	0·27	0·12	10·5	3·9	14·3	17·1
1941	0·16	0·29	0·06	12·7	3·6	16·2	15·1
1942	0·19	0·33	0·07	13·7	3·9	17·5	13·7
1943	0·18	0·32	0·08	14.5	4·2	18·7	12·3
1944	0·19	0·36	0·12	14·6	4·7	19·3	11·7
1945	0·18	0·36	0·12	13·8	5·3	19·2	11·8
1946	0·17	0·38	0·13	13·3	5·7	19·0	12·0
1947	0·18	0·38	0·13	12·9	5·7	18·5	12·4

average returns from unit fertilizer may therefore fall unless very great efforts are made to encourage the systematic manuring and liming of the poorer land. During the war this was achieved by issuing larger permits for the deficient soils. Nearly all farmers took their rations, but now there is no automatic stimulus to encourage farmers to purchase an adequate amount of fertilizer.

As some indication of the amounts likely to be used for the principal crops and kinds of grassland, an attempt has been made in Table 13 to build up an immediate fertilizer programme for the United Kingdom by combining 1947 crop acreages with average rates of dressing akin to those for crops in the war-time rationing schemes but including the special needs of deficient soils. The estimates for grassland are admittedly very rough and the average rates shown may soon be exceeded. It will be seen that even the modest average rates assumed call for substantial increases in fertilizer consumption beyond the war-time peak.

TABLE 13.

OUTLINE OF A FERTILIZER PROGRAMME FOR UNITED KINGDOM BASED ON 1947 CROP ACREAGES.

	1947 million acres	Average dressing cwts per acre			Total requirements thousand tons		
		N	P_2O_5	K_2O	N	P_2O_5	K_2O
Cereals	8·0	0·15	0·25	0·10	60	100	40
Potatoes	1·3	0·70	0·70	1·00	46	46	65
Sugar beet	0·4	0·70	0·60	0·60	14	12	12
Fodder crops ..	1·6	0·60	0·80	0·40	48	64	32
Vegetables	0·6	0·60	0·80	0·40	18	24	12
Tillage crops	11·9	0·31	0·41	0·27	186	246	161
Temporary grass ..	5·6	0·10	0·30	0·10	28	84	28
Permanent grass ..	12·4	0·04	0·20	0·02	25	124	12
Grassland	18·0	0·06	0·23	0·04	53	208	40
Total	29·9	0·16	0·30	0·13	239	454	201
Estimated consumption of fertilizers in 1947-8 ..					186	372	190

To supply the necessary fertilizers for the Agricultural Expansion Programme will put a heavy load on the fertilizer works, which have been running at high pressure for many years. One way out of the difficulty will be to use greatly increased amounts of ground rock phosphate for grassland and swedes in the wetter areas with acid soils. This would allow more water-soluble phosphates for the drier areas and basic soils. Britain is one of the few countries exporting nitrogen fertilizers at a time of an acute world shortage. The authorities responsible for allocations between countries have many difficult problems to handle, but British farmers have a high claim for priority on the grounds that they can obtain large and immediate returns in food by using more nitrogen fertilizer.

The figures in Table 12 for the consumption of liming materials from 1939 to 1948 reveal some unsuspected features. The total

consumption of liming materials increased rapidly in 1943 when the bulk of the ploughing-up had been done and many failures through soil acidity had been recognized. A large part of the additional material was in the form of ground limestone and the average grade (percentage of calcium oxide) fell from around 75% to 43%. The lower grade and the greatly increased area of arable land led to the odd result that at the peak of the liming campaign, when the country appeared to be dotted with white heaps or whitened fields, the average rate of liming arable land was no higher than in 1939. It amounted only to 2·0 cwts. CaO per arable acre. This is less than the figure commonly taken as the average annual loss of lime in drainage water from well-limed land. On this basis it would appear that the liming campaign had done little more than meet inevitable wastage. The position is not, however, quite so grave because much of the lime went to very acid land where the immediate effect was large and the annual wastage well below average because the soil remained acid even after liming. Nevertheless it must be admitted that the lime subsidy scheme of paying half or more of the delivered cost of liming materials has failed in ten years in its main task of removing one of the principal limiting factors to soil fertility and crop production. The whole question of liming needs to be reviewed and new methods devised to encourage farmers on acid soils to use more liming material. Spreading directly from lorries needs to be extended. It might be found possible to establish uniform prices for liming materials at the farm, as has been done for most fertilizers.

Future Developments in the Production and Use of Fertilizers.

It is too early to formulate any long-term policy in the production and use of fertilizers, but some general directions of future progress are fairly clear. Even though there were sometimes irritating local shortages of fertilizers, it would be wrong to conclude that the soils of the country were exhausted of plant foods during the war, and that the general level of soil fertility fell. Some fields certainly became plough-stale and weedy through growing cereals too frequently, and these should go down to leys to restore their structure and reserves of organic matter. Phosphate is needed for much of the permanent grass, especially for dairy cows and young stock, and many soils are short of potassium. These pressing requirements are, however, small by comparison with the over-all improvements in productivity and soil fertility resulting from improved cropping, draining, liming and manuring. Judging the whole country as a single estate or farm, any valuer would be bound

to conclude that it was a far more prosperous and improving concern than in the pre-war days of depression.

Apart from developments through fundamental research and new discoveries, it is possible to foresee some of the main directions in which technical investigations will proceed. The first task will be to obtain more knowledge of individual soils, crops, manures and systems of husbandry by surveys and field experiments. Generalisations can then be made for much more closely defined local conditions. Any one method of soil analysis must be expected to break down on widely contrasted soils in regions with quite different climates and systems of husbandry, but modified methods can be adapted for various local conditions, once a sufficient number of field experiments has been conducted and the soils classified and mapped. Field experiments are the vital link between farming and research. Long-term investigations on the cumulative and residual effects of different systems of cropping and manuring must be laid down at permanent experiment centres representing various agricultural systems, and large numbers of short-term field experiments in carefully co-ordinated series must be conducted on ordinary commercial farms.

The general trend in manuring is clearly towards more frequent small applications of concentrated materials by improved machines. Some day it may become possible to prepare slowly acting forms of synthetic nitrogen fertilizers to supplement the dwindling supplies of concentrated organic nitrogen fertilizers and the manurial residues from imported feeding stuffs. It seems unlikely that this country will be able to afford large imports of these materials, or that the poor soils of India, Africa and South America can be indefinitely " mined " to enrich our soils. These countries will need to process their farm products, so as to retain as much protein and other nutrients for their own people, stock and land, and to export mainly oils, fibres and starchy foods, which carry away only elements derived from the atmosphere.

Anhydrous ammonia with 82% nitrogen is the cheapest and most concentrated source of fertilizer nitrogen, but in Britain it does not appear to have been much used away from the works where it is made. In the United States it is shipped under pressure in tanks, and promising results have been obtained on a large scale by applying it directly below the soil surface through special drills. The application can be combined with cultivation or planting and the loss of lime from the soil is less than with equivalent amounts of sulphate of ammonia.

Great developments may be expected in the production of phosphate fertilizers. Until the last decade or so superphosphate

had no serious competitor except the by-product basic slag, but entirely novel methods are already in operation for producing alternative fertilizers from rock phosphate. Some of these processes were outlined on page 38. Much work is being undertaken to see whether there is any advantage in mixing superphosphate with various basic materials, *e.g.* lime, basic slag, or serpentine (a natural magnesium silicate), to produce a phosphate available to crops but less quickly inactivated in the soil.

In the United States anhydrous ammonia or concentrated solutions of ammonia, often reinforced with ammonium nitrate and urea, are added to superphosphate. In this way it is possible to use cheap forms of nitrogen which cannot be incorporated into mixtures containing water-soluble phosphate. The ammoniated superphosphate is easy to handle and store, and although much of the phosphate present is no longer water-soluble it appears to be just as active as that in ordinary superphosphate.

It is too early yet to assess the immediate prospects of these newer materials, but one point at least is clear. We suffer an unnecessary restriction by requiring our superphosphate and compound fertilizers to be valued in terms of their water-soluble phosphoric acid. In the early days of the industry water-solubility served to distinguish poorly made samples, but the industry is now so efficient that this test has outlived its usefulness. It has even become an obstacle to progress, because many of the new products have little water-soluble phosphate even though they are just as readily available to crops. In the United States, France and a few other countries an alternative test is based on extracting with ammonium citrate solution. Some other test than water-solubility must soon be introduced into our Fertilisers and Feeding Stuffs Act Regulations, in order that full advantage may be taken of current and future research.

The problems involved in investigating new methods of making available phosphates are so complicated and the technical resources required so elaborate, that they have been attacked systematically only by large chemical corporations, the U.S. Department of Agriculture and the Tennessee Valley Authority. These last two organisations have done most of the outstanding fundamental research on the chemistry of phosphate fertilizers, and have developed novel products of great potentialities. It may be noted that, at first, they both encountered considerable opposition from mixers of the older grades of compound fertilizers, who did not see why official bodies should enter the fertilizer industry. The world has ample reserves of phosphate rock and vast areas of land need phosphate fertilizer. The technical efficiency of making

and using phosphate fertilizers must be improved, and in some way the old suspicions between buyer and seller must be broken down. Research institutes and the National Agricultural Advisory Service with the good-will and assistance of farmers can test new and old products, and improve their practical use, but something more is wanted. The general planning and co-ordination of future supplies, so effectively carried out by Ministries of Supply and Agriculture during the war might be taken over by a central body, somewhat along the lines of the Agricultural Machinery Board, with adequate resources and staff for developing new forms of fertilizer and undertaking fundamental research.

APPENDIX A.

Fertilizer Prices in Great Britain from 1947
(Statutory Rules and Orders, 1947, No. 213).

1. All prices are per ton for not less than 6 ton lots, delivered to nearest station, except for muriate and sulphate of potash which are quoted at "importer's stores."
2. Prices are quoted for deliveries in March to June. For earlier deliveries prices per ton are reduced as follows :—

	Sulphate of ammonia, Superphosphate and Ground Phosphate Rock	All Compound Fertilizers
July	12/0	30/0
August	10/6	25/0
September	9/0	20/0
October	7/6	12/6
November	6/0	10/0
December	4/6	7/6
January	3/0	5/0
February	1/6	2/6
March to June	nil	nil

3. Adjustments for each 1% P_2O_5 : phosphate rock 1/6, superphosphate 2/6, basic slag 3/- per ton.

TABLE 14.

	N%	sol. P_2O_5%	total P_2O_5%	K_2O%	per ton £ s. d.
Sulphate of ammonia ..	20·6	—	—	—	10 8 0
Superphosphate ..	—	18	—	—	5 19 0
Ground phosphate rock	—	—	25	—	5 6 6
Basic slag	—	—	7	—	2 1 6
" "	—	—	12	—	2 16 6
" "	—	—	18·3	—	3 15 6
Muriate of potash ..	—	—	—	40	9 4 0
" " " ..	—	—	—	45	10 7 0
" " " ..	—	—	—	50	11 10 0
" " " ..	—	—	—	55	12 11 6
" " " ..	—	—	—	60	13 13 0
Sulphate of potash ..	—	—	—	48	18 15 0
" " " ..	—	—	—	50	19 15 0
National Compound					
No. 1	7	6·5	7	10·5	10 14 6
No. 2	9	6·75	7·5	4·5	10 8 6
No. 3	6	11	12	—	9 5 6
No. 4	4	13·75	15	—	9 3 6
Concentrated Compound					
No. 1	12	—	12	15	16 13 6
No. 2	14	—	16·5	10	17 15 0
Ammonium phosphate					
	13·8	—	42·3	—	21 2 0
	11	—	48	—	21 5 0

APPENDIX B.

THE RESIDUAL MANURIAL VALUE OF FERTILIZERS, LIMING MATERIALS AND FEEDING STUFFS.

Summary of Report of a Conference appointed by the Ministry of Agriculture. The Report was published in the Journal of the Ministry of Agriculture, 1946, Vol. 53, pp. 163-170.

Fertilizers.

Fertilizers are classified according to their availability and the average duration of their effects, and then valued by using the appropriate unit prices in Table 15.

TABLE 15.

COMPENSATION VALUES FOR THE RESIDUAL EFFECTS OF UNIT PLANT FOOD IN FERTILIZERS.

(*i.e.* price for each 1 per cent of a ton).

	After 1 (growing seasons)	After 2 (growing seasons)	After 3 (growing seasons)
	s. d.	s. d.	s. d.
Nitrogen			
(*a*) Inorganic (as in sulphate of ammonia, compound fertilizers)	nil	nil	nil
(*b*) In dried blood	nil	nil	nil
(*c*) In all other organic forms specified in the First Schedule of the Fertiliser and Feeding Stuffs Act (*e.g.* hoof, meat, bone) ..	5 0	2 6	nil
Phosphoric Acid			
(*d*) Soluble by official methods (as in superphosphate, basic slag) ..	4 0	2 0	1 0
(*e*) Insoluble by official methods ..	2 0	1 0	6
(*f*) Total (or insoluble) in bone products	3 0	1 6	9
(*g*) Total in other materials (*e.g.* mineral phosphate).	2 0	1 0	6
Potash			
(*h*) Total	2 6	1 3	nil

Lime and Limestone.

All compensations are based on delivered costs after the recovery of subsidies. Compensation is paid on an eight-year principle, *i.e.* one-eighth is subtracted each year after application. The full delivered cost (less subsidy) is taken as the basis for compensation where the liming was done at moderate rates or in accordance with recommendations by the National Advisory Service. But where a farmer has used heavy rates or unduly expensive forms without such advice, dressings containing more of any form of lime than the equivalent of 40 cwt. pure calcium oxide (CaO) per acre are to be valued at the cost (less subsidy) of this quantity as either burnt lime or ground limestone, according to the form used.

Feeding Stuffs.

The average compensation values worked out from the appropriate unit prices given below are subject to the adjustments listed in Table 16 according to the conditions under which the foodstuffs are fed, the urine conserved and the farmyard manure made, stored and used.

Conditions are to be regarded as satisfactory where the urine is well conserved and the dung well made, where reasonable precautions are taken against losses in the dung heap, and where the dung is applied to land likely to give normal responses.

TABLE 16.

ADJUSTMENT OF AVERAGE COMPENSATION VALUES TO VARIOUS CONDITIONS.

	Foodstuffs fed to milking cows	Foodstuffs fed to stock other than milking cows and working horses
(1) Fed directly on the land ..	average	add one-third
(2) Fed under cover—conditions satisfactory ..	average	add one-third
(3) Fed in open yards—conditions satisfactory ..	subtract one-third	average
(4) Conditions unsatisfactory	subtract up to one-half	subtract up to one-half

For the average conditions the unit prices in the original foodstuffs are given in Table 17.

TABLE 17.

AVERAGE COMPENSATION VALUES FOR THE RESIDUAL EFFECT OF UNIT PLANT FOOD IN FOODSTUFFS.

(*i.e.* price of each 1 per cent of a ton).

	Before one crop has been removed	After one crop has been removed
	s. d.	s. d.
Nitrogen	3 0	1 6
Phosphoric Acid	3 0	1 6
Potash	3 0	1 6
In compound cakes and meals		
Albuminoids (proteins) ..	10	5

Compound cakes and meals are treated separately because warranties do not normally declare the percentages of phosphoric acid and potash.

Straw and other bulky materials.

For straw and other bulky manures, an allowance may be made for the combined nutrient and mechanical values of 12s. 0d. per ton before one crop has been removed and of 6s. 0d. per ton after one crop has been removed. Where straw has been sold off the farm a dilapidation may be made at the rate of 12s. 0d. per ton in the last year of tenancy and of 6s. 0d. per ton in the last year but one.

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